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BENJAMIN FRANKLIN (1706–1790).

(From the portrait by Duplessis—kindness of Dr. Joseph Rosenbach.)

A celebrated American philosopher, statesman, diplomatist, and scientist; founded the Philadelphia Library, the American Philosophical Society, and the University of Pennsylvania. In 1752, by means of a kite in a thunderstorm, proved that lightning is an electrical discharge; invented the lightning-rod; suggested the one-fluid theory of electricity

THE

ELEMENTS OF PHYSICS

BY

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PREFACE

In revising Dr. Houston's "Elements of Natural Philosophy," the attempt has been made to preserve the method of presenting the subject which gave the book its great attraction. In order to bring it up to the requirements of the present day High School and College Preparatory work, it has been necessary to introduce much more of the mathematical form of treatment than the earlier book contained. It is believed that all that is necessary for such work has been introduced, while for those who do not care for this method, or for whose pupils it is considered too difficult, it will be found that much of the mathematics has been put in smaller type, or is most fully developed in the Appendix.

Many new drawings have been added, mostly in the form of diagrams, as this is believed to be the best method for teaching purposes. The problems have been greatly increased in number and graded in difficulty. No attempt has been made to cover all the subjects of physics, as the book is intended for one year's work. It has been the reviser's experience that when the subject matter covered is too large, the effect upon the pupil is disheartening. The material presented, however, covers all the necessary requirements of the field the book is intended to occupy.

It is, of course, understood that whenever possible the lectures and recitations should be accompanied by suitable laboratory experiments.

The thanks of the reviser are gratefully tendered to Dr. E. A. Partridge, of the Central Manual Training School, for his constant advice and assistance as the work of revision was carried out; and to Dr. G. F. Stradling, of the Northeast Manual Training School, for many suggestions for the improvement of the book.

A. N. S.

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THE ELEMENTS OF PHYSICS

PART I

MATTER AND ENERGY

CHAPTER I

MATTER

1. Definition of Matter.—Matter is anything which occupies space and prevents other matter from occupying the same space at the same time.

Experiment 1.—Fill a tumbler to the brim with water. Quietly drop a stone into the water, and observe that some of the water runs out of the tumbler.

Some of the water runs out of the tumbler, because both the stone and the water cannot occupy the same space at the same time. The tumbler is already filled with water, and when the stone is dropped in, it falls to the bottom and causes a volume of water to run out equal to the volume of the stone.

If a thing merely occupies space, but does not prevent other things from occupying the same space, it is not matter.

All matter occupies space in three dimensions—that is, it has *length*, *breadth*, and *thickness*, or, in other words, *volume*.

If matter could exist with length and breadth but no thickness, an infinite quantity of such matter could be put in a given, limited space, such as a cubic inch. The thinnest film of water, or the thinnest leaf of gold, has thickness, and, therefore, must possess a definite volume.

Iron and gold are kinds of matter, since they both occupy space and prevent other matter from occupying the same space at the same time.

Air and water are kinds of matter. A body moved through air or water does not occupy the same space the air or water does, but merely pushes the air or water out of its way, and then occupies the space it has thus cleared for itself.

Experiment 2.—Let the sunlight fall on the tumbler filled with water. Observe that, though the light fills the tumbler, no water runs out.

Water and light, then, apparently fill the goblet and occupy the same space at the same time. Light, therefore, is not matter.

2. The Senses.—We acquire knowledge by means of our senses, and by them we become aware of the existence of matter, which we can see, hear, feel, taste, or smell.

All matter, however, is not visible. Air is invisible. Heat converts water into invisible vapor. On losing this heat, vapor becomes visible as dew, rain, snow, mist, fog, or cloud.

Our senses act as the paths through which impressions are received from without; thus, light entering the eye enables us to see the color and form of objects; by the sense of touch we are enabled to distinguish the nature of the surface and the texture of objects; by the senses of taste and smell we are enabled to select the pleasant and wholesome from the disagreeable and noxious; and, finally, by our hearing we are enabled to understand the thoughts of others when expressed in speech.

3. Substances. Elements.—Different kinds of matter are called *substances*. Iron, wood, water, milk, and air are substances.

Substances are either *elementary* or *compound*.

Elementary substances, or elements, are those which have never yet been resolved or separated into more than one kind of matter.

Compound substances are those which are formed by the union of two or more elementary substances, and which may be resolved or separated into two or more elements.

We now know that some of the elements are actually capable of division into simpler parts. It is highly probable that many of the elements are compound. Indeed, in the opinion of some, all the elements are compounds of a single substance.

Gold is an elementary substance. We cannot, by any known means, break it up or separate it into anything but gold. Water is a compound substance, since we can separate it into hydrogen and oxygen; or, by mixing hydrogen and oxygen together in the right proportions and igniting, we can produce water.

All known compound substances are formed by various combinations of about eighty simple or elementary substances.

Any definite quantity of matter is called *a body*. Bodies may be either large or small; thus, both the earth and a grain of sand are bodies, since they are definite quantities of matter.

4. Properties of Matter.—Different kinds of matter possess various peculiarities or properties, by means of which we are enabled readily to recognize them. Thus, gold can be distinguished from marble, because its color and its density are different; gold may also be drawn out into wire, or beaten into thin sheets, while marble cannot be so drawn or beaten.

5. Changes in Matter.—Matter is subject to changes. These changes are of two distinct kinds:

(1) *Physical changes*, or those which may occur in any substance without altering its chemical composition.

(2) *Chemical changes*, or those which cannot occur in any substance without altering its composition.

Experiment 3.—Take a piece of steel, such as a common needle, and, after examining it carefully so as to note its peculiarities, rub it once or twice with a magnet. The needle will now have acquired a property it did not possess before; it will attract iron filings to it; but if we again examine the needle carefully, we cannot see that it has lost any of the properties it previously possessed. This change is a physical change, for the substance in undergoing the change has not lost its characteristic properties and remains of the same composition.

Experiment 4.—Expose the needle for some time to damp air. Observe that it becomes covered with a brown rust, which is formed by oxygen, a substance in the air, combining with the iron of the needle. Observe that the rust so formed resembles neither of the things out of which it was formed, since one of them was the iron of the needle itself, and the other, an invisible gas. If the needle is heated in a flame, it loses its polish and becomes coated with a darker substance very similar to the rust, being a combination of the iron of the needle with the oxygen of the air. This change is a chemical change, since both bodies have lost the properties or peculiarities by which they are generally recognized and a new substance has been formed.

6. Physics and Chemistry.—*Physics* is the name given to the study that considers the causes and effects of the physical changes which take place in matter.

Chemistry is the name given to the study that considers the causes and effects of the chemical changes which take place in matter.

7. Phenomenon.—Anything that happens in the course of nature is called a *phenomenon.*

As commonly used, the word phenomenon means something unusual or strange; but as used in science, it means anything which happens. The fall of a leaf, the shining of the sun, the fall of a raindrop, and the growth of a plant, are called phenomena.

8. Cause and Effect.—All natural phenomena are produced by certain causes; for example, unsupported bodies fall: here all we see is the effect, namely, the motion. The cause of the motion is the attraction which the earth has for the body.

An effect may itself be the cause of some succeeding effect; thus, the body, in falling to the earth, may give some of its motion to another body which it strikes, and this effect may in turn be the cause of some subsequent effect, and so on indefinitely.

The causes which produce natural phenomena can be traced to the action of certain forces, one of the most important of which is *gravity.*

9. Natural Law.—The relation between cause and effect is constant and invariable. The same cause, acting in the same way, always produces the same effect. Thus, unsupported bodies always fall to the earth; a steel needle rubbed against a magnet always becomes magnetic, the same needle, unless specially protected, always becomes covered with rust when exposed for some time to damp air or heated in a flame.

When, by observation, we discover the cause of any natural phenomenon, and ascertain the order in which cause and effect follow each other, this order, expressed in language, forms what is called a *natural law.*

Physics has for its object the study of natural laws. This definition, it will be seen, embraces the study of all natural phenomena; but physics is generally restricted to the study of the laws concerning physical changes.

10. Method of Study.—There is only one way in which we can discover natural laws, and that is by *observation.* If we wish to know what effect will follow a certain cause, we must make the trial and observe what happens. If, after repeated careful trials or experiments, we obtain the same effects, we may conclude that we have discovered the law.

11. Energy is the ability to produce phenomena or to do work. Natural phenomena never occur of themselves. They are always due to *energy acting on matter.* Whenever matter is set into motion or whenever the amount or direction of its motion is changed, energy is expended or work is done.

A log of wood cannot be sawn or cut unless energy is expended or work is done. A ball is not driven from a gun until the force of the gunpowder or other explosive causes energy to be expended on it. Water cannot pass off into invisible vapor until the heat-energy from the sun or from some other source acts upon it.

12. The Indestructibility of Matter.

Experiment 5.—Burn a piece of paper. Observe that the paper disappears, and that the heat developed is apparently lost.

In reality there has been no loss. By the process of burning, the paper has been changed into invisible gases. The quantity of matter in the paper has not been changed by burning. The heat liberated has acted on the surrounding matter and produced changes therein. An interesting but rather more difficult experiment is as follows: Place a small piece of yellow phosphorus in a porcelain crucible and put the crucible in a wide-mouthed flask. Cork the flask very carefully and weigh it quickly. Warm gently, until the phosphorus ignites. When cold, reweigh and the weight will be found to be unchanged. The oxygen of the air in the bottle has combined with the phosphorus to produce a new substance, oxide of phosphorus. But no matter has been destroyed, so the total weight remains unchanged.

There exists on the earth a definite quantity of matter. During the changes that occur the quantity of matter can neither be increased nor diminished. Matter may disappear in one form, but only to reappear in some other form.

CHAPTER II

ATOMS AND MOLECULES. PROPERTIES OF MATTER

13. Molecules.—

Experiment 6.—Fill two tumblers, one with water and the other with dry sand. Observe that even to the sharpest vision, the water appears to fill the entire space within the tumbler, or, in other words, the water appears to be absolutely continuous, while the sand does not fill the entire space within the tumbler, but is distinctly granular, and contains spaces between the separate grains.

When examined by the most powerful microscope, the water in the tumbler appears to be absolutely continuous. Nevertheless, there are ample reasons for believing that water, like all matter, is not continuous, but is granular; or is composed of exceedingly small separate quantities of matter called *molecules*.

It is easy to cut a piece of gold-leaf or tin-foil into exceedingly small pieces with a pair of scissors or with a sharp knife. When these pieces are so small as to render it difficult to further divide them, it is possible, by placing one of them under a microscope capable of magnifying, say 500 times, to cut it into 500 pieces, and if the magnifying power of the microscope be increased, it is possible to carry the subdivision still further.

The particles of gold or of tin obtained in this manner present all the appearances peculiar to gold or to tin. They have the same color and luster, and their hardness and other peculiarities are the same. Though exceedingly minute, these particles are not molecules, but in all probability consist of many millions of molecules.

If we could continue dividing and subdividing the particles of the gold or of the tin, we would finally reach the molecules which are believed to be indivisible by any physical means.

14. Atoms.—Molecules can, however, be divided by chemical means into still smaller particles called atoms.

Each of the eighty different kinds of elementary substances or elements is formed of the same kind of atoms. It is believed that the atoms of each kind of elementary substance have the same size and weight, but that the atoms of different kinds of elementary substances have different sizes and weights; thus, all atoms of iron are of the same size and weight, no matter from what part of the world the iron may come. In the same manner, all atoms of gold are of the same size and weight; but the atoms of iron are neither of the same size nor of the same weight as the atoms of gold.

It was long thought that atoms were indivisible by any means; in fact, the very word atom means this. Recent experiments have shown that the atoms of some elements are spontaneously throwing off still smaller particles called corpuscles or electrons. The rate at which this takes place cannot be altered by even the greatest extremes of temperature.

It is believed that atoms do not exist in a free state in ordinary matter, but under the influence of the attractions or affinities they possess for one another they unite in definite groups called molecules. Though larger than atoms, the molecules are too small to be seen even by the aid of the most powerful microscope.

Atoms are not infinitely small, but possess definite volume; *i. e.*, they have length, breadth, and depth, or occupy space in three directions.

Kelvin estimates that if a drop of water were magnified to the size of the earth, the molecules would be larger than small shot, but smaller than cricket balls. The atoms would, therefore, be still smaller.

It has been estimated that a cubic centimetre (equal to about the one-sixteenth part of a cubic inch) of air at ordinary pressure and temperature contains twenty quintillions of molecules, *i. e.*, 20,000,000,000,000,000,000; or, as it is sometimes written, 2×10^{19}, or 2 followed by 19 ciphers.

Neither the atoms nor the molecules touch one another, but are separated by spaces called *pores*. All matter is, therefore, granular, the smallest particles being the electrons of which the matter is composed. The next smallest particles of matter are the atoms and next to these are the molecules, or groups of atoms.

Molecules may consist either of atoms of the same element, or of atoms of different elements; that is, molecules may be either *elementary* or *compound.*

The number of separate atoms in a molecule varies with the kind of atoms that unite to form the molecule. A molecule of water has three atoms; a molecule of ordinary sugar has forty-five atoms; and a molecule of aniline blue has seventy-two atoms.

A molecule of water consists of one atom of oxygen combined with two atoms of hydrogen. Should one of the hydrogen atoms be taken away from the molecule of water, there would be left an incomplete group of atoms, consisting of one atom of hydrogen and one atom of oxygen. Such a group of atoms would not have its attractions completely satisfied, since it could combine with another atom like hydrogen. It forms what is called a *radical.*

15. Varieties of Attraction.—Besides the attractions or affinities that atoms possess for one another, as a result of which they unite and form molecules, the molecules also possess attractions for one another and form groups of molecules called *masses.* The separate masses also possess mutual attractions.

There are, therefore, three kinds of attraction:

1. *Atomic attraction*, or *chemical affinity*, whereby the atoms unite and form groups of atoms called molecules.

The rusting of iron, the burning of coal, and the explosion of gunpowder are examples of atomic attraction.

2. *Molecular attraction*, whereby the molecules come together and form what are called masses.

Molecular attraction is called *cohesion* when it exists between molecules of the same kind, and *adhesion* when it exists between molecules of different kinds.

The molecules of a piece of chalk cohere to one another, but adhere to the molecules on the surface of a blackboard.

3. *Molar* or *mass attraction*, which exists between different masses of matter.

Mass attraction is generally known as the *attraction of gravitation.*

An unsupported body falls to the earth by reason of molar attraction or gravity.

16. Essential and General Properties of Matter.—There are certain properties which are possessed exclusively by the atoms of matter; there are other properties which are possessed in common by atoms and molecules, and still other properties which are possessed in common by atoms, molecules, and masses.

Properties possessed in common by all kinds of matter are called the *general* properties of matter.

There are other properties that are possessed only by particular kinds of matter. These may be called *specific* properties of matter.

17. The general properties of matter are impenetrability, extension, inertia, divisibility, porosity, compressibility, and expansibility.

18. Impenetrability means that no two portions of matter can occupy the same space at the same time. If a stone is dropped into water, the two substances do not both occupy the same space, but some of the water is pushed aside to make room for the stone. It is by reason of impenetrability that the volume of an irregular solid may be readily obtained by measuring the volume of water displaced when the solid is immersed in the water.

Impenetrability appears to apply only to matter in masses. Electrons or corpuscles seem to have the power of penetrating larger bodies of matter. In reality, however, they only pass through the pores or spaces between the atoms or molecules.

19. Extension means that all bodies occupy space in three directions; viz., in length, breadth, and thickness.

A piece of tissue paper or of gold leaf which may be so thin as to transmit light may seem to have but two dimensions. But if enough pieces are piled together, some easily visible thickness will become apparent, so each piece must have some thickness.

20. Units of Measurement.—In the United States and Great Britain the dimensions of a body, that is, its length, breadth, and thickness, are measured in certain units called *inches*, *feet*, *yards*, and *miles*. In other parts of the world, and in scientific writings generally, dimensions are measured in *metres*, or in decimal multiples or submultiples of a metre.

The metric system of length originated in France in 1799. The unit of length, the metre, was intended to be one-ten-millionth part of a quadrant of the meridian passing through Paris; *i. e.*, of the distance between the Equator and the North Pole. The metre is now properly defined as the distance between two marks on a bar of metal kept at Paris when at the temperature of melting ice. A metre is equal to 39.37 inches.

English Measure.

Measures of Length.	*Measures of Surface.*	*Measures of Volume.*
12 in. = 1 ft.	144 sq. in. = 1 sq. ft.	1728 cu. in. = 1 cu. ft.
3 ft. = 1 yd.	9 sq. ft. = 1 sq. yd.	27 cu. ft. = 1 cu. yd.
1760 yd., or 5280 ft. = 1 mile.		

French Measure.

Measures of Length.

1 metre	=	39.37	English inches	or 3.281 ft.
1 decametre, or 10 metres	=	393.7	“	“
1 hectometre, or 100 metres	=	3937.	“	“
1 kilometre, or 1000 metres	=	39370.	“	“ or 1093.6 yd.
1 decimetre, or $\frac{1}{10}$ metre	=	3.937	“	“
1 centimetre, or $\frac{1}{100}$ metre	=	.3937	“	“
1 millimetre, or $\frac{1}{1000}$ metre	=	.03937	“	“ or $\frac{1}{25}$ in. nearly.

A centimetre is approximately four-tenths of an inch.

In the French system, the *litre*, which is generally taken as the standard unit of volume, is the volume of a cube, the length of the edge of which is one decimetre, or ten centimetres.

Measures of Area or Surface.

1 square metre	=	1550.	sq. in., or 10.764 sq. ft.
1 square decimetre	=	15.5	"
1 square centimetre	=	.155	"
1 square millimetre	=	.00155	"

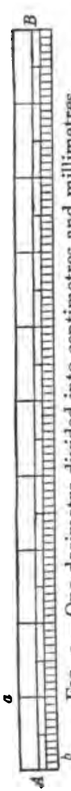

FIG. 1.—One decimetre divided into centimetres and millimetres.

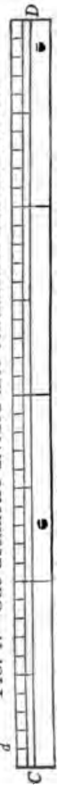

FIG. 2.—Four inches divided into tenths.

Measures of Volume.

1 cubic metre	=	61023.	cu. in., or 35.32 cu. ft.
1 cubic decimetre, or litre	=	61.02	"
1 cubic centimetre	=	.06102	"

Values of English in French Units.

1 inch	=	2.54 centimetres nearly.
1 foot	=	30.48 centimetres nearly.
1 yard	=	91.44 centimetres nearly.
1 mile	=	160934 centimetres nearly.

Subdivisions of a Litre.

1 millilitre	=	.06102	cubic inch.
1 centilitre	=	.6102	"
1 decilitre	=	6.102	cubic inches.
1 litre	=	61.02	"

Figure 1 represents the actual length of the decimetre, and Fig. 2, the actual length of four inches. Since a decimetre equals 3.937 inches, it is but a trifle shorter than four English inches. From *A* to *B* is one decimetre; from *A* to *a* is one centimetre, of which there are ten in one decimetre or in the whole length of *A B*. From *A* to *b* is one millimetre, of which there are ten in every centimetre.

From *C* to *D* is four English inches; from *C* to *c* is one inch; from *C* to *d*, is one-tenth of an inch. There are about twenty-five millimetres in one inch.

One *micron* equals the one-millionth part of a metre, or the one-thousandth part of a millimetre. The micron is much used as a unit of length in microscopy, the smallest visible particle being about the tenth of a micron in size.

21. Inertia.—A body never begins to move, never stops moving, nor changes the direction in which it is moving, nor the velocity with which it is moving, unless force of some kind acts upon it. In other words, matter can do nothing of itself toward changing its condition, either of rest or of motion.

If we attempt to move a comparatively large body from a state of rest, as, for example, a wheel capable of revolving freely on an axis, we shall find it necessary to exert our strength for some time before we can get the wheel moving rapidly; that is, we find that a body at rest apparently offers a resistance to changing its state of rest. On the other hand, when the wheel has been set in motion, we shall be obliged to exert our strength, but this time in the opposite direction, before we can bring the wheel to rest again; that is, we find that a body in motion apparently offers a resistance to changing its state or condition of motion, just as a body at rest offers a resistance to changing its condition of rest.

By the *inertia* of matter is meant its tendency to continue in whatever condition it may be, whether at rest or in motion, until some force acts upon it. It follows, from the property of inertia—

That a body at rest will continue at rest forever, unless some force acts upon it.

That a body in motion will continue in motion forever, unless some force acts upon it.

It is easy to understand that a body at rest will continue at rest forever, until acted upon by some force, since such is a matter of common observation. But it is difficult, at first, to believe that the same thing is true of a body in motion. A rough marble when rolled over a rough floor soon comes to rest. If rolled over a smooth floor, it continues to move for a longer time. A smooth steel ball would roll for a very long time over a smoother floor. Hence we are quite justified in saying that if there were no resisting force it would move forever.

The earth moves through the apparently empty space around the sun, where there is nothing to stop its motion, at a rate of more than a million and a half miles per day.

Perpetual motion, in the case of a body like the earth moving through a space in which it meets no resistance, necessarily exists from the fact that the moving body has inertia. On the earth the perpetual motion of a machine, as ordinarily understood, is an impossibility, since the motion of the machine is resisted both by the friction of its supports, and of the air, or other medium, in which it is moving. Therefore, the idea that a machine could ever be invented which would perpetually do useful work of itself is quite impossible.

22. Examples of Inertia.—When a train of cars begins to move, some time is required before full speed is attained, on account of inertia. When, however, the train has attained this speed, considerable force at the brakes must be exerted to stop it.

Since energy is indestructible, before a moving body can be brought to rest, it must expend an amount of work equal to that which was done on it to cause it to move. Cannon-balls owe their great destructive power to the fact that a large amount of work has been done upon them in the gun; viz., by the explosion of gunpowder, hence they overcome considerable resistance before stopping.

If we jump from a rapidly moving car, we are likely to fall, because, on reaching the ground, the motion of our feet is stopped, while the rest of our body continues to move forward by its inertia. Again, a running jump will carry us much farther than a standing jump, because, if we first run rapidly in the direction in which we wish to jump, the motion thus given to the body will help to carry it in that direction.

Experiment 7.—Stand a book upright on its end on a sheet of paper. Pull the paper slowly and the book can be moved without falling. Observe that motion is gradually imparted to the book. While the book is moving, suddenly stop moving the paper. Observe that the book will fall forward, since its top keeps on moving after that part resting on the paper has stopped. Pull the paper quickly on starting. Observe that the book falls backward, because the part resting on the paper is moved forward before the top commences to move.

Experiment 8.—Suspend a heavy weight by a cord and attach a fine thread to it. Pull slowly on the thread, and the weight may be put in motion without breaking the thread. Then give a sudden pull and the thread will be broken without giving much motion to the weight. This shows that time is required to put a body in motion.

23. All Matter Possesses Inertia.—All matter, whether living or without life, possesses inertia.

We are conscious of having to exert our strength before we can move about from place to place. Thus, we move an arm by means of its muscular force. When we set our bodies in rapid motion, as in running down a hill, we find it necessary to exert considerable force in order to stop suddenly.

Experiment 9.—Place a card over the open mouth of a bottle, and on the card over the center of the mouth place a lead shot. Give the card a sudden horizontal blow, as by a " flip " of the finger, and the card will fly off while the shot will drop into the bottle. Before the shot had time to get into motion, its support was removed and it dropped.

24. Resistance to Motion.—A body moving through air or water can advance only by pushing the air or water out of its way. Since both air and water possess inertia, they cannot move themselves out of the way, and, therefore, require force to act upon them. This force is exerted by the moving body, and diminishes its energy of motion. Resistances of this kind are called *fluid resistances*, and are impediments to motion.

If the resistance of the air did not retard the fall of a raindrop, its velocity on reaching the earth would be sufficient to render it as fatal to the person it struck as a bullet shot from a rifle.

25. Friction.—When bodies are slid or are rolled over one another, they meet another resistance or impediment to motion.

Even the smoothest surfaces we can obtain are marred by irregularities. When one body is slid or rolled over another, the projections of the one, fitting into the depressions in the other, cause a resistance to motion. Besides the irregularities of the surface, whenever two bodies are brought near each other, they attract or tend to hold on to each other. The resistance to motion produced in this way is called *friction.*

Friction results either by sliding or by rolling one body over another. Rolling friction is less than sliding friction, because, in rolling, the elevations of one of the contact surfaces are lifted out of the depressions in the other, while in sliding they are moved bodily over one another. In sliding friction the force required to start the body is greater if it has been resting on the other body for some time.

Experiment 10.—Insert a screw-hook into the side of a brick. Place the brick flat on a table. Attach one end of a string to the hook, and pass it over a small pulley, as shown in Fig. 3. Add weights to the end of the string to start the brick moving. Disregarding the friction of the pulley, these weights equal the starting friction between the brick and the table. Place a second brick on the first. The pressure on the table is doubled. Observe that the weight required to start the two bricks in motion will be about twice as great as in the first case.

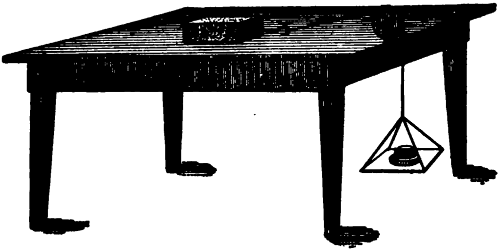

FIG. 3.—Friction apparatus.

26. Laws of Friction.—The friction between two surfaces increases with the pressure between them.

Within certain limits, friction is independent of the area of contact surfaces. Thus, if the brick used in experiment 10 be placed upon the table on its edge instead of on its face, the same weight will be required to start it; for, although the surfaces in contact are now smaller, the weight on each square inch of surface is greater.

The amount of friction between two surfaces depends upon the nature of the surfaces. In general, friction is greater between surfaces of the same kind than between surfaces of different kinds.

Friction is diminished by filling the irregularities of the surfaces with grease or oil.

A body is slippery if it produces but little friction when moved over another body.

The ratio between the force required to keep the body moving and the pressure normal to the surface is known as the *coefficient of sliding friction.*

27. **Divisibility** is that property of matter by which it may be separated or divided into smaller parts.

Masses are divisible into smaller masses. They are also divisible into molecules. Molecules are divisible into atoms. Atoms, according to the latest view, are made up of electrons, but although some of them are constantly splitting up, we cannot control the action.

The following examples will show the wonderful extent to which it is possible to carry the division of matter: Gold can be beaten into leaves so thin that it would take three hundred thousand, placed one upon the other, to make a pile one inch thick, and yet, each of these leaves may be cut into very small pieces.

A grain of musk will for years continue to give off odorous particles to the air around it without decreasing perceptibly in weight.

A very small quantity of certain coloring-matters will give a decided tint to a large quantity of water. Now, since the water so colored may be divided into a great number of parts, in each of which the color is distinctly visible, the quantity of coloring-matter in each part must be exceedingly minute.

The microscope has revealed to us the existence of organisms so small that millions of them can easily move in the space of a cubic inch without touching one another.

28. Porosity.—Neither the atoms which form molecules, nor the molecules which form masses, remain in contact with one another, but are separated by spaces called pores.

Pores are either—

1. *Inter-atomic; i. e.*, between the atoms that form the molecules.

2. *Inter-molecular; i. e.*, between the molecules that form the masses.

3. *Inter-molar; i. e.*, between the particles or little masses that form the greater masses.

The inter-molar pores are the largest, and may be readily seen, as in most woods or in sponges.

The inter-molecular pores are so small that they cannot be seen, even with a powerful microscope.

The inter-atomic pores are probably still smaller.

All matter is porous, that is, it possesses inter-atomic and inter-molecular pores; some matter possesses also inter-molar pores.

The inter-molecular pores are largest in gases, smallest in solids, and of intermediate size in liquids.

Though inter-molecular pores cannot be seen, yet we know that they exist, because matter, when in mass, is compressible, expands on being heated, and contracts on being cooled.

Experiment 11.—Fill a tumbler to the brim with alcohol. Slowly place in the alcohol several handfuls of loose, absorbent cotton. Observe that though a bulk of the cotton several times the bulk of the alcohol is put in the already full tumbler of alcohol, yet none of the alcohol runs out.

Here the molecules of the alcohol and absorbent cotton mutually penetrate each other's inter-molecular pores.

Experiment 12.—Measure out 100 cu. cm. each of water and of alcohol and then mix them thoroughly. The volume will be found to be less than 200 cu. cm. Here the molecules of the water and alcohol mutually penetrate each other's inter-molecular pores.

29. Expansibility.—Matter *contracts* or decreases in bulk by a loss of heat, and *expands* or increases in bulk by an addition of heat. Generally, gases expand more than liquids, and liquids more than solids, with the same addition of heat.

Experiment 13.—If an empty glass bottle be held mouth downward in a plate of water, as shown in Fig. 4, so that the mouth is just under the water, and the hand be made to cover as much of the outside of the bottle as possible, the heat from the hand will cause the air inside the bottle to expand, so that the bottle will no longer be able to hold it all, and the air will be seen to escape from the mouth of the bottle in bubbles.

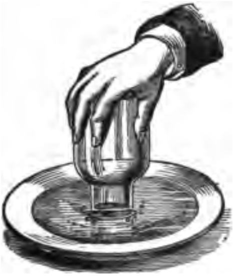

FIG. 4.—Expansion of air.

PROBLEMS

1. The polar circumference of the earth through Paris is approximately 24,860 miles. From this calculate the value of a metre in feet, if it were equal to one-ten-millionth of a quadrant.
2. Calculate your height in metres.
3. The summit of Mount Washington, the highest elevation in the State of New Hampshire, has an altitude of 1916 metres above mean tide level. Find this altitude in feet.
4. The gauge of most railroads is 4 ft. 8½ in. Express this in metres.
5. The Krag-Jorgensen repeating-rifle, adopted for the U. S. army, has a calibre of 0.3 inch, and imparts an initial velocity

of 2000 feet per second to its projectile. Express the calibre in metres and millimetres, and the initial velocity in metres per second.

6. The river span of the Brooklyn bridge is 1595 ft. 6 in. Express this in metres.

7. The area of land upon the surface of the globe is approximately 137.3 million sq. kilometres. Express this area in square miles.

8. The breadth of a red corpuscle, in normal human blood, varies between the $\frac{1}{8200}$ and the $\frac{1}{8500}$ part of an inch. Express this range in centimetres.

9. The amount of blood in the body of a full-grown man being say 680 cubic inches, and there being approximately 5,000,000 of red blood-corpuscles in a cubic millimetre, find the number of red blood-corpuscles in his body.

10. Express 14.506 m. (*a*) in mm. (*b*) in km. (*c*) in cm.

CHAPTER III

THE CONDITIONS OF MATTER

30. States or Conditions of Matter.

Experiment 14.—Gradually heat a lump of ice in a suitable glass vessel. Observe that the ice melts, and, if the heat be continued, the water boils and passes off as vapor as soon as a certain temperature is reached.

Water may, therefore, exist—

1. As a *solid* in the form of ice.
2. As a *liquid* in the form of water.
3. As an *invisible vapor* in the form of steam.

Most matter may exist in the three conditions above named; viz., the solid, the liquid, and the gaseous.

The change of liquids into gases or vapors by the action of heat is called *vaporization.*

When any quantity of vapor loses the heat which converted it into vapor, it again becomes a liquid. This process is called *liquefaction* or *condensation.*

When a gas is subjected to pressure, its molecules are forced together and their freedom of motion reduced.

If the temperature is not too high, this pressure, when sufficiently great, will change the gas into a liquid. Gases may also be liquefied by cold. Generally, both cold and pressure are employed in their liquefaction.

Formerly, certain gases were called *incoercible* or *permanent,* since they had not been liquefied by cold or pressure. By subjecting them to intense cold and pressure combined these too have now been liquefied so that there are no gaseous substances which are incoercible.

There is for every gas a definite temperature above which no pressure, however great, can convert it into a liquid. This is known as the critical temperature.

31. The Kinetic Theory of Matter.—It is believed that the molecules of matter are never at rest, but that in the densest solids, as well as in gases and liquids, they are moving to-and-fro toward and from one another with exceeding rapidity.

The lengths of the paths through which the molecules move are greater in liquids than in solids, and still greater in gases.

The molecules, in their to-and-fro motions, frequently collide or strike against one another. The effect of these collisions is to change both the direction and the velocity of their motion. The collisions are more frequent in solids than in liquids, and in liquids than in gases. In solids the molecules, in their to-and-fro motions, do not change their relative positions, adjacent molecules remaining adjacent molecules. In liquids and in gases, however, the molecules slip over or move past one another, so that adjacent molecules do not remain adjacent molecules. Thus, taking the students in a school-room to represent individual molecules in one plane of a solid, if they moved to and fro in their seats without changing their seats, they would always retain the same relative positions. The same students at play in a playground would represent the condition of molecules in one plane of a liquid or gas; for here the students would not retain their relative positions during their movements.

The molecules in their to-and-fro motions are kept at certain average distances from each other by the action of the force of molecular attraction tending to draw the molecules together, which is more or less opposed by the action of heat. Heat causes the molecules to vibrate, and this vibration tends to cause the molecules to move apart, overcoming their molecular attractions.

The different conditions of matter, the solid, the liquid, and the gaseous result from the different degrees with which these attractive and repulsive forces act on the molecules, and the consequent difference in the freedom of movement possessed by these molecules.

32. Solids.—In solids, molecular attraction is strong; consequently the molecules in their to-and-fro motions resist any force tending to change their relative positions. Moreover, the paths through which the molecules move are limited.

Solids have a shape because their molecules strongly cohere.

The intensity of molecular attraction varies in different solids. A piece of paper or a match-stem may easily be pulled into smaller pieces, but, if we take a piece of sheet iron, no thicker than the paper, and try to pull it to pieces, we shall find that it will require a much greater force than can be exerted by the unaided hands.

A steel wire, so thin as to be practically invisible at a distance of several yards, may be strong enough to hold a man's weight.

In soft wax or butter the molecules are held together so feebly that but little force is required to change the shape of the mass. These substances in some respects resemble liquids.

33. Fluids.—Substances whose molecules move freely over one another are called *fluids*. There are two kinds of fluid substances; viz., *liquids* and *gases*.

34. Liquids.—In liquids, the force of molecular attraction is weaker than in solids. The molecules are not held so strongly together, and move through longer paths. Moreover, when acted on by any force, they can easily move or slide over one another.

From the great freedom of motion of their molecules, liquids possess no definite shape, but assume that of the vessel in which they are kept, except on their *free* or *upper surface*, which is sensibly horizontal or level. A quantity of water poured into a bottle will take the shape of the inside of the bottle, and will keep that shape as long as it continues in the bottle; but if poured into a cup, plate, or tumbler, it will at once take the shape of the inside of the cup, plate, or tumbler.

35. Gases.—In gases there is such a freedom of motion that the matter has neither shape nor volume of its own. When placed in a vessel, the gas expands until it fills it, and has no upper bounding layer, as is the case with a liquid.

The difference between the three states of matter may be briefly stated in this way:

Solids have both size and shape of their own.

Liquids have size but no shape of their own.

Gases have neither size nor shape of their own.

Matter, however, exists in all kinds of intermediate states. As is usual in nature, we cannot pass sharply from one condition of matter to another, but rather pass through intermediate states. Thus it is easy to classify steel, water, and air as typical examples of the three states. But putty, molasses, and tar show gradations of properties which make their classification less easy.

Liquids like molasses and tar which do not flow readily are called viscid or viscous liquids. Liquids like alcohol and water, which flow readily, are called mobile liquids.

Some solids, such as the metals, when subjected to sufficient pressure, exhibit many of the phenomena of flow. In the process of wire-drawing a stout bar of cold iron or copper may be drawn, without fracture, into a wire many hundred times the length of the original bar.

A disc of metal, put under a powerful coining press, is caused by the pressure to flow into all the cavities of the die, thus accurately assuming the precise impression. Heavy blocks of stone, when subjected to long-continued pressure, may be considerably bent or flexed without fracture.

36. Influence of the Pressure of the Air on Liquids.—Were it not for the pressure of the air, many bodies which are now liquids would become gases. Water and many other liquids, when placed in a space from which all the air has been removed, will turn into the gaseous state. Gaseous bodies that are formed from liquids in this way, or by the direct action of heat, are called *vapors*.

In many liquids the forces of molecular attraction and repulsion are not in equilibrium until the pressure of the atmosphere adds its force to that of attraction.

In gases the to-and-fro paths of the molecules are so great that they are beyond each other's attractive forces. The molecules, therefore, move in straight lines until they either collide against one another, or against the side of the vessel in which they are contained.

Gases tend to expand indefinitely, and, since their molecules are beyond the range of mutual attraction, they produce a pressure against the walls of the vessel that contains them.

Unlike liquids, gases contained in vessels possess no free, limiting, upper surface.

When a gas is enclosed in a bottle, it presses upward against the cork, as well as against the sides and base.

The earth's atmosphere is densest near the surface because the attractive force of the earth causes the upper layers of air to press with considerable force on the lower layers. Toward the upper limits of the air the atmosphere is very rare. Were it not for the attraction of the earth, the atmosphere would entirely leave the earth.

When a balloon rises very high above the earth's surface, the gas it contains expands, and occupies a much greater bulk than it did near the surface. If a balloon, at the time of its ascent, contains too much gas, it may burst on reaching moderately great heights, unless some arrangement is provided for the escape of the excess of gas.

37. Influence of Heat on the Condition of Matter.—Solids are changed into liquids by the action of heat. They are then said to have been *melted* or *fused.*

Some substances are easily melted or fused. Ice, for example, melts at quite a low temperature. Butter softens when brought into a warm room. Other substances are melted or fused only by the action of intense heat. Cast iron requires the heat of a blast furnace to melt it. Substances that are difficult to melt or fuse are called *refractory substances.*

When molten substances lose the heat which caused them to fuse, they again become solid. This process is called *solidification.* Thus water solidifies or freezes when it loses sufficient heat. Cast iron is obtained in any desired form by pouring it, when melted, into moulds, in which it solidifies on cooling. All liquids are changed into solids when they lose sufficient heat.

CHAPTER IV

FORCE AND MOTION

38. Inertia.

Experiment 15.—Attach a heavy weight to a string and hold it so that it can swing like a pendulum. Observe that an effort is required to start it swinging, and that, when swinging, an effort is required to stop it.

In other words, on account of its inertia, the weight will neither of itself begin swinging, nor of itself immediately cease swinging, but requires some force to act on it. Stated more generally, a body never begins to move, or alters the direction or speed of its motion, unless some force acts on it.

39. Force is that which tends to cause a body to begin to move, or to alter either the direction or the velocity of its motion.

A great variety of natural forces exist. Some of the most important of these are:

1. The force of gravitation, which causes unsupported bodies to fall to the ground.
2. The force of molecular attraction.
3. The force of atomic attraction, or chemical affinity.
4. The forces of electric and magnetic attraction and repulsion.

40. Dynamics is that branch of physics which treats of forces and their effects.

Dynamics may be divided into—

Statics, which treats of forces that counterbalance one another, and which, therefore, produce no motion or change of motion; and—

Kinetics, which treats of forces that do not counterbalance, and which, therefore, cause motion or change of motion.

41. Motion and Rest Relative.—Absolute rest is impossible on the earth, since all things thereon are being carried with the earth, both as it rotates on its axis and as it revolves around the sun. We may, however, speak of a body as being at rest when it is not changing its position in relation to neighboring bodies.

A person sitting in a moving train of cars is at rest as regards the car, since he does not change his position relatively to other objects in the car, although both he and the car are in rapid motion.

The person, moreover, is breathing, the blood is moving through his heart, arteries, veins, and capillaries; and the molecules in his body, and in the inanimate objects around him, are in rapid to-and-fro motions. Absolute rest, therefore, is an impossibility.

42. The Specifications of a Force.—Three things must be known in order to measure the effects produced by any force:

1. The *point of application*, or the point at which the force acts.
2. The *direction* in which the force acts.
3. The *intensity* with which the force acts.

Forces are generally represented by straight arrows; the intensity of the force is represented by the length of the arrow; the direction of the force, by the direction in which the arrow points; and the point of application of the force is considered as being situated at that end of the arrow which is placed against the string of the bow.

Thus, in Fig. 5, the body *A*, has its weight, or the force with which it is pulled downward by the attraction of the earth, represented by the length of the arrow *g B*. The direction of gravity is vertically downward, as indicated by the direction in which the arrow points, and the point of application of the force is indicated by the point *g*.

When forces are represented by arrows, a certain portion of the length, as, for example, one inch, or one centimetre, is taken to represent a certain value or unit of force. Thus, in the figure, if the arrow *g B* were two inches, or two centimetres, long, the figure might represent a force of two units acting at the point *g*, in the direction of *g B*.

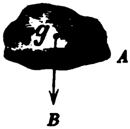

FIG. 5.

43. The Direction in which the Force Acts.—

Experiment 16.—Take hold of a book and draw it toward you. Observe that the book moves toward you. Push it; observe that it moves from you.

The direction in which a force acts determines the direction in which the body moves.

44. The Point of Application of the Force.—

Experiment 17.—Place one end of a ruler against a book lying on a table, and push the book. Observe that the kind of motion the book acquires depends on the part touched by the ruler. If the ruler be placed near the middle of one of the edges of the book, a push will move it straight forward in the direction you are pushing; but if the ruler be applied near a corner, although the book may still advance when pushed, it will, at the same time, turn partly around.

The point at which a force is applied determines the nature of the motion produced.

45. The Intensity of the Force.—

Experiment 18.—Push the book with more force in one instance than in another; observe that its motion is more rapid when the greater force is acting upon it.

The intensity of a force which causes a motion determines the rapidity of that motion, the time remaining the same.

46. The **unit of time** is a second, or the $\frac{1}{86400}$ part of a mean solar day; *i. e.*, the day represented by ordinary clocks.

47. **Velocity.**—The velocity of a body is the rate at which it moves, and may be expressed as the distance through which it would move in a given time if the rate were not changed. The distance is generally measured in feet or centimetres, and the time in seconds; thus, by a velocity of six feet per second, we mean a velocity that will carry the body through six feet in one second of time.

In order to compare velocities, some standard or unit of velocity is taken. This unit is either one foot per second, or one centimetre per second, or one mile per hour.

The relations between the distance passed over by a body moving at a uniform velocity, the velocity with which it moves and the time, may be expressed algebraically by the equation:

$$S = V \times t \quad (1)$$

Here S stands for space passed over, V for velocity, and t for time. From this we derive the equations—

$$V = \frac{S}{t} \text{ and } t = \frac{S}{V}.$$

The velocities in feet per second, and miles per hour, for a number of objects are given in the Appendix.

48. Acceleration.—The rate of change of velocity of a body is called its acceleration. If the change of velocity is the same for each second, the acceleration is *uniform*. If the velocity increases, the acceleration is *positive;* if it decreases, the acceleration is *negative.* A train as it leaves a station and "gets up speed" has positive acceleration, as it slows down to make a stop, it has negative acceleration.

If a is the acceleration or change in velocity per second, then

$$V_f = a \times t \quad (2).$$

That is, the final velocity at the end of a given time is equal to the gain in each second, multiplied by the number of seconds. From this—

$$a = \frac{V_f}{t} \text{ and } t = \frac{V_f}{a}.$$

If the body starts from rest when the velocity is zero, the average velocity during the time of motion is—

$$\frac{0 + at}{2} = \tfrac{1}{2}\, a \times t = V_a.$$

In equation (1) V was average velocity; we may, therefore, substitute this value for that in equation (1) and we have—

$$S = \tfrac{1}{2}\, at \times t = \tfrac{1}{2}\, at^2 \quad (3)$$

From this

$$a = 2\frac{S}{t^2} \text{ and } t = \sqrt{2\frac{S}{a}}.$$

If we wish an equation from which t has been eliminated, we may obtain one by combining (2) and (3), when we find:

$$S = \frac{V^2}{2a} \text{ or } V = \sqrt{2aS}.^1 \quad (4)$$

49. Mass.—If one body is heavier than another, it will be found that more force is required to give the heavier body a given velocity in a given time.

The mass of a body must not be confounded with its weight. The mass of a body, or the quantity of matter it contains, is proportional to the number of its molecules; that is, if we double the number of its molecules, we double the mass of the body; if we halve the number of its molecules, we halve the mass of the body. The mass of a body is the same in all latitudes, and would be the same at the centre of the earth as at the surface. The weight of a body is the measure of the mutual attraction between the body and the earth; this varies slightly with the latitude, being somewhat greater at the poles than at the equator, and at the centre of the earth a body would have no weight.

It is evident, therefore, that in all latitudes two equal masses will counterbalance each other on a balance.

50. Measurement of Force.—There are two systems in common use for measuring force—the gravity method and the absolute method. The gravity unit of force is the weight of a mass, such as the pound or gram. As gravity varies somewhat at different places on the earth, these units are not exactly constant.

The absolute units of force, being independent of gravity, are constant in value. The C. G. S. absolute unit of force is called the dyne. The dyne is that force which, acting on the mass of one gram, will give it an acceleration of one centimetre per

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[1] $V = at \quad t = \frac{V}{a} \quad t^2 = \frac{V^2}{a^2}.$

$$S = \tfrac{1}{2}\, at^2 = \tfrac{1}{2}\, a \times \frac{V^2}{a^2} = \frac{V^2}{2a}.$$

second. A freely falling body acquires a velocity of 980 centimetres per second. Therefore, the weight of a gram is equal to 980 dynes; for since the weight of a gram, acting upon a mass of one gram, gives it 980 times as much acceleration as would be given to the same mass by one dyne, the weight of a gram must be equal to 980 dynes. A dyne is, therefore, $\frac{1}{980}$ of the weight of a gram.

This may be expressed by the equation—

$$f = m \times a. \quad (5)$$

Here f = force, m = mass, a = acceleration.

The intensity of any force is measured by the rapidity of motion which it gives to a certain mass. If two unequal forces act upon equal masses for equal times, the force which produces the more rapid motion is the stronger. If equal forces act upon unequal masses for equal times, the greater velocity will be given to the smaller mass.

51. Laws of Motion.—The following laws, known generally as Newton's laws of motion, express the principal phenomena of mass motion.

First Law of Motion.—*A body at rest will continue at rest, or a body in motion will continue in motion, in a straight line with a uniform velocity, until acted on by some external force.*

The first law of motion is a mere statement of the property of inertia, and is sometimes called the *law of inertia.* Since matter has no ability either to start itself moving, to stop moving, or to change the direction of its motion; if at rest, it must continue at rest; or, if moving, it must continue moving, until acted on by some external force.

52. Second Law of Motion.—*Any change in the direction or in the amount of motion is proportional to the force acting, and takes place in the direction in which the force acts.*

The amount and character of the motion produced by any force depends on the direction and magnitude of that force. The same force acting for equal times on two masses, one twice as great as the other, will impart to the smaller mass a velocity twice as great as to the larger.

A horse can pull a light wagon much faster than it can pull a heavy cart. An empty wheelbarrow can be pushed much faster on a level than a heavily loaded wheelbarrow. A boy can run much faster when unimpeded than when carrying a weight on his back.

The amount of motion of a body, therefore, depends not only on the quantity of matter the body contains, but also on the intensity of the force causing its motion and the time during which this force acts.

53. Momentum.—The *momentum* of a moving body is the amount of motion it possesses.

The momentum of a moving body, or the quantity of motion it possesses, is equal to the mass of the body multiplied by its velocity.

This is expressed by the equation—

$$M = mV. \quad (6)$$

M = momentum, m = mass, and V = velocity.

In the C. G. S. system, unit momentum is that of unit mass (one gram), moving with unit velocity (one centimetre per second).

A floating chip is harmless when it strikes the sides of a small boat, but a floating log may crush the boat if caught against a wharf or other fixed obstacle. Even a powerful ship, caught between two large ice-bergs moving in opposite directions, may be as completely crushed as is an egg-shell when trodden on.

If, while in motion, we strike our bodies against any fixed obstacle, as a tree, the injury received will depend on the speed with which we are moving. If walking at a moderate speed, the injury would probably be but slight; if running, we may break a bone; if thrown from a carriage, or from a car while in rapid motion, we may lose life.

54. Another Phrasing of the Second Law of Motion.—*A force produces the same effect on a body whether that body be moving or at rest; whether it be the only force acting; or whether other forces are also acting on the body.*

A weight dropped to the floor of a rapidly moving car strikes the floor directly under the place from which it fell. The car-floor does not move from under the weight while it is falling, since the weight is moving forward as rapidly as the car.

A mounted acrobat at a circus, in jumping through a hoop, does not jump forward; if he did he would be carried over the horse's head. He simply jumps up into the air, and, since his body has the same onward velocity as the horse, he falls again on the horse's back, just as the weight, dropped to the floor of the car, strikes the floor directly under the place from which it fell.

55. Third Law of Motion.—*To every action there is always an equal and contrary reaction.*

When one jumps from a small boat to the wharf, the reaction pushes the boat out from the wharf. If the boat is a large one, as a ship, the reaction is still the same, but now the mass being so large, the velocity is very small.

When a falling body strikes the earth, it imparts to the earth a momentum equal to its own. The motion imparted to the earth, however, is exceedingly small as compared with that of the falling body, because the mass of the earth is so much greater.

A ball, shot from a gun, produces a recoil or kick, in which the momentum or amount of motion in the gun is equal to that of the ball and is opposite in direction. The mass of the gun is so much greater than that of the ball that the actual velocity imparted to the gun is comparatively small.

56. Varieties of Motion.—When a body moves through equal distances in equal times, its velocity is said to be *uniform.* The earth rotates on its axis with uniform velocity, so that if we look at a star through a telescope, it passes across the field of view with uniform velocity.

When a body moves through unequal distances in equal times, its velocity is said to be *variable.*

If the velocity of the body changes at a uniform rate, we say that its motion is *uniformly accelerated.*

When the velocity regularly increases, the acceleration is said to be *positive.* When the velocity regularly decreases, the acceleration is said to be *negative.*

Excluding the effect of the resistance of the air, an example of uniformly accelerated motion is seen in the case of a falling body, in which gravity is constantly adding uniformly to the motion which the body has already acquired; its motion, therefore, is uniformly accelerated.

An example of a uniformly retarded motion is seen in a body thrown vertically upward. Such a body must have a uniformly retarded motion, because gravity is constantly decreasing its motion uniformly.

Bodies whose motion is either uniform or varied may move in straight lines or in curves; that is, their motion may be *rectilinear* or *curvilinear*.

Rectilinear motion is that in which the body moves in a straight line.

Curvilinear motion is that in which the body moves in a curve.

In rectilinear motion the body continues to move in the same direction. In curvilinear motion, the body is constantly changing its direction of motion. When a body moves around a line, as a wheel on its axis, the motion is said to be *rotary*.

It is evident from what has been stated concerning the first law of motion that a rectilinear motion does not require the constant action of a force, while a curvilinear motion can take place only by reason of constant action of a force.

57. Components and Resultants.—A body cannot move in more than one direction at the same time. No matter, therefore, how many forces may simultaneously act on a body, their combined action can produce motion only in one direction; and this motion could have been produced by a single force of sufficient intensity acting in the proper direction.

Any single force which will produce on a body the same effect as a number of separate forces is called the *resultant force*.

The motion produced by the action of a number of separate forces is called the *resultant motion*.

The separate forces are called the *component forces*.

58. Composition of Velocities.—When a body is acted upon at the same time by two or more different forces, so that motion is produced, the actual motion is not the result of any one force, but is a resultant of all the forces.

Since a velocity has both direction and magnitude, it may be represented by a straight line. The determination of the actual velocity of a body by the use of lines to represent the component velocities is called *composition of velocities.* Various cases may arise, which may be briefly stated as follows:

(1) *The Velocities are in the Same Straight Line.*—The actual velocity is the algebraic sum of the components and its direction is that of the greater. If a boat which in still water moves at the rate of 10 miles per hour goes up stream against a current of 3 miles per hour, its actual velocity is at the rate of 7 miles per hour: $10 - 3 = 7$.

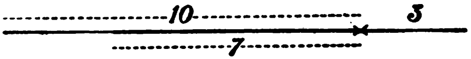

FIG. 6.

(2) *The Velocities are not in the Same Straight Line.*—They may be represented by lines taken as the two sides of a parallelogram. The diagonal of the parallelogram will represent both the magnitude and the direction of the resulting velocity.

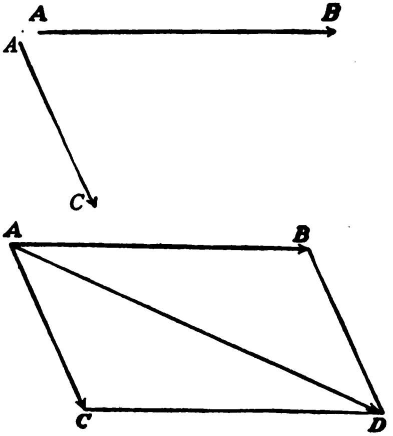

FIG. 7.

Let AB and AC (Fig. 7) represent the two velocities. With these as sides construct the parallelogram $ABCD$. The diagonal AD will represent the resulting velocity in both magnitude and direction. If the angle between the velocities is a right angle, the value of the resulting velocity is found by simple geometry. (The square on the hypothenuse is equal to the sum of the squares on the other two sides.) If the angle is not a right angle, the length of the diagonal is found by trigonometry or by construction.

(3) *There are More than Two Velocities.*—Any two are reduced to one by Case 2, and this method is continued until the final diagonal gives the resultant velocity of all the motions.

59. Composition of Forces.—When several forces act at the same time on a body, their combined effect may be replaced by a single force. The method adopted for finding the direction and intensity of this single force is called the *composition of forces.*

In order completely to know a force three things are necessary: (1) Its point of application; (2) its direction; and (3) its magnitude of force. As a straight line is also known by these specifications, such a line may be employed so as to picture the force. The point from which the line starts will then represent the point of application of the force; the direction in which it is drawn will represent the direction in which the force acts; while the length of the line will represent the magnitude of the force.

The two or more forces may act:

1. In the same straight line.
2. At some angle with one another; *i. e.*, not in the same straight line.
3. In the same direction, but not in the same line; *i. e.*, parallel to one another, as a pair of horses drawing a wagon.

60. Forces Acting in the Same Straight Line.—Two cases may arise:

1. The separate forces may act in the same direction, and thus aid one another.
2. The separate forces may act in opposite directions, and thus oppose one another, as in the game called "the tug of war."

When the forces act in the same direction, the resultant is equal to their sum. When two forces act in opposite directions, the resultant is equal to their difference; and in the latter case, if the two forces are of equal intensity, they will be in *equilibrium*, and the body will be at rest so far as their action is concerned.

61. Parallelogram of Forces.—

Experiment 19.—Let a pupil draw a straight line on a blackboard. Let another pupil draw another line in any direction, beginning at the point from which the first line was started, say at right angles to it. Now let both together hold the chalk and endeavor at the same time to draw the same lines as before. Observe that a line will now be drawn between the other two. This line is called the *resultant.*

When a body is acted on by two forces in directions at an angle with each other, it will not move in the direction of either force, but in some direction between them; that is, the resultant will lie somewhere between the two components.

Thus, suppose a solid body at *D* (Fig. 8) be simultaneously acted on by two forces, *DC* and *DB*, in the directions indicated by the arrows, and of such intensities that each acting alone would in the same time move the body to the points *C* and *B* respectively. Then, under the action of both forces the body would in this time be carried to *A*.

The value and direction of the resultant *DA* are determined as follows: from the point *C*, the line *CA* is drawn parallel to *DB*, and from the point *B*, the line *BA* is drawn parallel to *DC*. If, now, their point of intersection, *A*, be connected with *D* by a straight line *AD*, this line will represent the resultant of the two forces *DC* and *DB*.

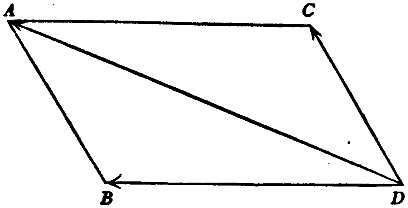

FIG. 8.

The figure *A B C D*, being a four-sided figure bounded by parallel lines, is called a *parallelogram*, and this construction is generally called *the parallelogram of forces.*

This method of determining the direction and intensity of the two forces is a particular case of the composition of forces before referred to.

The parallelogram of forces affords another example of the fact, already stated, that when two or more forces simultaneously act on the same body, each produces the same effect as if it acted alone. Thus, by the force *DC*, the body would be carried from *D* to *C*, or its equal from *B* to *A*; by the force *DB*, acting for an equal time, it would be carried from *D* to *B*, or its equal, from *C* to *A*. We see that each force has produced the same amount of effect as if it acted alone; for, while the force *DC* has carried the body through a distance equal to *DC*, the force *DB* has carried it through a distance equal to *AC*.

62. Equilibrant.—When the forces acting upon a body do not produce motion, the body is said to be in equilibrium. In such a case one of the forces may be considered as balanced against the others, and is called the *equilibrant*.

In Fig. 9 the force *AE* is the equilibrant of the forces *AC* and *AB*. It is evidently equal in magnitude to the resultant *AD*, and has the same point of application, but is opposite in direction.

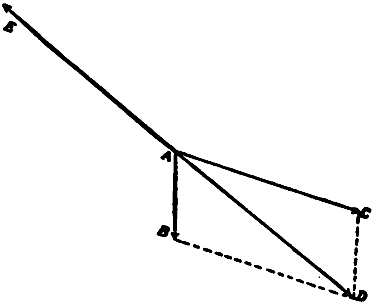

Fig. 9.

63. More than Two Forces.—If more than two forces act at the same time on a body, the single resultant may be found by a repetition of the parallelogram of forces.

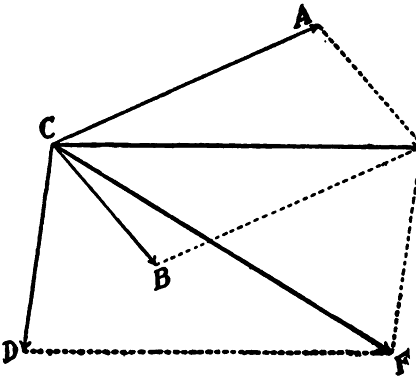

Fig. 10.

If the three forces, *CA*, *CB*, and *CD* (Fig. 10), act at the same time on the point *C*, their resultant may be found by first taking any two, as *CA* and *CB*, and finding the resultant *CE*. The force *CE* is then compounded with *CD*, and the resultant *CF* is the single force equivalent to all three forces, and, therefore, their resultant. The same method may be applied to any number of forces.

64. Parallel Forces.—When two parallel forces act in the same direction, their resultant is always equal to their sum; but the point of application of the resultant does not coincide with the points of application of either of the two forces.

When the two forces are of equal intensity, the resultant is situated midway between them; but when they are of unequal intensity (Fig. 11), the point of application of the resultant *EF* lies nearer to the larger force *AB*, at such a point that its distances from the two forces *AB* and *CD* are inversely proportional to the intensities of the two forces.

Thus, a team of two horses abreast, tugging at the whipple-tree of a vehicle, produces a resultant at the centre of the whipple-tree if they exert equal forces. If they exert unequal forces, the resultant shifts to the side of the stronger horse. If one horse is twice as strong as the other, the resultant is twice as far from the weaker horse as from the stronger one.

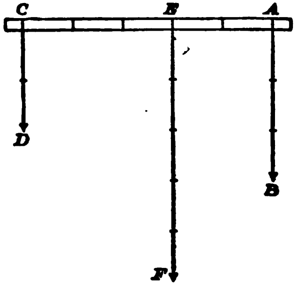

Fig. 11.

65. Resolution of a Force.—By the *resolution* of any force is meant the finding of the components which will produce that force. This process is the reverse of that of the composition of forces.

Any number of single components acting on a given point may be compounded into a single resultant, and any single force may be resolved into any number of component forces. If, however, the direction and magnitude of the resultant of two forces are known, and the direction and magnitude of one of its components are known, the direction and magnitude of its remaining component may be determined. Thus, suppose a certain force has the magnitude and direction of *AD* (Fig. 12), and that one of its components has the magnitude and direction of *AB*, to find the direction and magnitude of its other component complete the parallelogram *ABDC*, and *AC* will represent the direction and intensity of its other component.

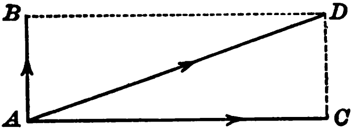

FIG. 12.

66. Centrifugal Force.—The inertia of a moving body, if unchecked, will cause the body to continue moving in a straight line forever. To stop its motion, or to change the direction of its motion, some force must act on it.

A stone tied to a string and whirled around will continue moving in a circular path as long as the string is held in the hand; but if we let the string go, the stone will no longer move in a circle, but will fly off in a straight line in the same direction as that in which the stone was moving at the time the hand released the string.

The force exerted in a direction outward from the centre, by a body moving in a circular path, is called the *centrifugal force*. The force which is exerted from without toward the centre is called the *centripetal force*. If the centripetal force ceases, the body will move in a straight line; and at the same time the centrifugal force will cease, since it is a consequence of the rotation.

The motion of the earth around the sun affords a good instance of the so-called centrifugal and centripetal forces. In consequence of the motion originally given it the earth is constantly tending to move away from the sun. The sun, however, is constantly attracting the earth: and these two causes make the earth move in an almost circular path around the sun.

67. Laws of Centrifugal Force.—The laws of centrifugal force, considered in relation to a small body rotating uniformly about a fixed centre, are as follows:

1. The centrifugal force is proportional to the mass of the rotating body.

2. The centrifugal force is proportional to the square of the velocity of the rotating body.

If the mass of the body be doubled, twice the amount of force will be required to keep it from moving away from the centre of rotation. If the velocity of the body be doubled, four times the force will be required to keep it from moving away from the centre of rotation.

The formula for centrifugal force is—

$$F_c = \frac{m \times V^2}{r}, \quad (7)$$

which gives the result in absolute units where m = mass, v = velocity, and r = radius of the circle in which the motion takes place.

Since $W = mg$, we have $m = \frac{W}{g}$, therefore,

$$F_c = \frac{W \times V^2}{g \times r}, \quad (8)$$

which gives the result in gravity units.

For derivation of this formula see Appendix.

68. Examples of Centrifugal Force.—Drops of mud thrown by centrifugal force from the wheels of a carriage in rapid motion fly off in straight lines. Grindstones and flywheels of engines, when in very rapid rotation, are sometimes burst by the action of centrifugal force. The tendency of the different portions of the wheel to continue moving in the direction in which they are moving at any given moment becomes, eventually, stronger than the cohesion of the particles, and the stone or wheel flies into a number of pieces, which move with considerable velocity in different directions.

In a centrifugal dryer, as used in laundries, the wet clothes are placed in a perforated basket which is revolved at a high rate of speed. The water is thrown off, while the clothes are prevented from flying off by the wire cage.

The shape of the earth is not that of a perfect sphere. The equatorial diameter, or the distance through the centre at the equator, is somewhat greater (about one-third of one per cent.) than the polar diameter, or the distance through the centre at the poles. This bulging of the earth at the equator was caused by the action of centrifugal force.

When a train rounds a curve, there is a tendency to leave the track and fly off at a tangent. Therefore, the outer rail is raised so that this tendency may be overcome.

PROBLEMS.

1. The distance between the Pennsylvania stations at Jersey City and Philadelphia is 89.6 miles. The Limited Express runs the distance in 1 hour and 59 minutes. Assuming its speed to be uniform between these points, what would be its velocity in miles per hour?

2. What would be the velocity of the above train if it made the run between the two cities in 1 hour and 30 minutes?

3. The velocity of light is 186,414 miles per second. What is its velocity in kilometres per second?

4. How long would it take a carrier pigeon to fly between New York and Philadelphia (89.6) miles, assuming its velocity to be 78 miles per hour?

5. What is the momentum of a 50-pound hammer moving at a velocity of 1½ feet per second?

6. A mortar discharges a 300-lb. projectile with a velocity of 800 feet per second. What is its momentum at this velocity in lbs.-ft. per second?

7. A man weighing 150 lbs. rides a bicycle weighing 25 lbs. at a speed of 20 miles per hour. What is the momentum of the man and bicycle together, in lbs.-ft. per second?

8. A balloon rises 500 ft. per minute and at the same time is blown along horizontally 400 ft. per minute. What is the actual rate of motion of the balloon?

9. Two forces in the ratio of 4 to 3 act perpendicularly to each other upon a point and produce a resultant force of 25 lbs. Find the value of the forces.

10. Find the magnitude and position of the resultant of two parallel forces of 16 and 24 lbs. respectively, which act in the same direction and whose points of application are 10 ft. apart.

11. Two men carry a 200-lb. weight by means of a rail 5 ft. long. Where must the weight be placed so that one of the men shall carry 75 lbs. and the other 125 lbs., neglecting the weight of the rail.

12. Resolve a force of 200 lbs. weight into two equal components at right angles to each other.

13. What force can be resolved into two components at right angles to each other, one of which shall be 40 and the other 120 lbs. weight?

14. A man can row a boat across a stream one-half a mile wide at the rate of 3 miles per hour. If he wishes to land at a point directly opposite, in what direction must he row and how long will it take him if the current is moving at the rate of 4 miles per hour?

15. Resolve a force of 40 lbs. weight into two components acting at an angle of 60° to each other.

16. A mass of 15 lbs. is moving with a speed of 25 ft. per second in a circle the radius of which is 5 ft. Find the force in lbs. weight which tends to break the string.

17. A mass of 75 grams is whirled around by means of a string 2 m. long. If it goes around three times in two seconds, find the tension on the string in grams weight.

18. A locomotive whose mass is 25 tons rounds a curve which is part of a circle whose radius is half a mile with a velocity of 25 miles per hour. What is its centrifugal force?

CHAPTER V

GRAVITATION

69. Gravity.—Unsupported bodies fall to the earth because they are attracted toward it by a force called the force of *gravity*, which is the attractive force one mass of matter exerts upon another.

The real nature of gravity is not understood, but, from repeated observation and experiment, we believe that every particle of matter in the universe acts as though it attracted every other particle of matter.

It is certain that the earth attracts the moon, but how it does so across absolutely empty space is not easy to understand. Although gravity apparently acts at a distance, yet the fact that the universal ether occupies and fills even what are ordinarily called empty spaces, has led to the belief that the phenomena of gravitation are essentially connected with this medium.

70. Weight.—The weight of a body is due to the action of gravity on the matter the body contains. A quart of water has twice the weight of a pint, because it contains twice as much matter for gravity to act upon.

A body placed on any support exerts a pressure on such support proportional to its weight.

This pressure is due to the attraction between the earth and the body.

71. Density.—If different kinds of matter, such as an apple, a block of wood, or a piece of iron, be cut into blocks of the same size, it will be found that these blocks have different weights. Since the weight of a body is due to the action of gravity on the matter it contains, it is evident that, as indicated by their weights, the same volumes of different substances contain different quantities of matter.

By the density of a substance is meant the mass or quantity of matter contained in a unit volume of that substance. It is evident, therefore, that equal volumes of different kinds of matter contain different masses or different quantities of matter. The denser a substance is, the greater the quantity of matter it contains in unit volume.

Thus, the density of sugar is the mass or quantity of matter contained in one cubic centimetre of sugar. The density of lead is greater than the density of sugar, and the attraction of the earth on a cubic centimetre of lead is greater than the attraction of the earth on a cubic centimetre of sugar; *i. e.*, the lead weighs more per unit volume.

72. English and French Systems of Weight.—The unit of weight, both in the United States and in England, is the pound. Unfortunately, the pound is of two distinct kinds; viz., the *pound avoirdupois* and the *pound troy.* The one seven-thousandth part of a pound avoirdupois or the five thousand seven hundred and sixtieth part of a pound troy is called a grain. Although the grains are the same in both pounds, their other subdivisions are different; in the pound avoirdupois there are 16 ounces; in the pound troy, 12 ounces.

In France and throughout Europe generally the unit of weight is the *gram.* This unit has various decimal multiples and submultiples. The gram was intended to be the weight of a cubic centimetre of water at the temperature of its greatest density; viz., at 39.2° F., or 4° C. It is now properly defined as the one-thousandth part of the weight of a piece of metal, the standard kilogram, kept in Paris. The difference between this and the weight of one cubic centimetre of water at 4° C. is so slight that it may be neglected for most calculations.

The gram is equal to about 15.432 English grains. The table of mass is as follows[1]:

10 milligrams = 1 centigram
10 centigrams = 1 decigram
10 decigrams = 1 gram
10 grams = 1 decagram
10 decagrams = 1 hectogram
10 hectograms = 1 kilogram

73. Law of Universal Gravitation.—The law of universal gravitation was discovered by Sir Isaac Newton, an English philosopher. It may be stated as follows:

The attraction between any two particles of matter in the universe is directly proportional to the product of their masses, and inversely proportional to the square of their distance apart.

One thing is said to be *directly proportional* to another when it increases in the same ratio that the other increases. If the mass of one body be 2, and that of another be 3, the attraction between them being directly proportional to the products of their masses would be 6. If the masses be 4 and 6, the attraction will be 24, or four times as great as in the case of the two bodies first referred to.

One thing is said to be *inversely proportional* to another when it increases in the same ratio that the other decreases. Thus, if one is made twice as great, the other becomes half as great. If at a certain distance the attraction between two bodies is represented by 8, then if this distance be made twice as great, the attraction would be but 2; viz., inversely as the square of the distance. This law may be expressed by the equation

$$F_g = a \frac{m\,m^1}{d^2}. \qquad (9)$$

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[1] **Multiples and Subdivisions of the Gram.**

		Grams.		Grains.	Oz. avoir.	Lbs. avoird.
1 kilogram	=	1000	=	15432.34	35.274	2.2046
1 hectogram	=	100	=	1543.23	3.5274	0.22046
1 decagram	=	10	=	154.32	0.35274	
1 gram	=	1	=	15.43	0.035274	
1 decigram	=	0.1	=	1.543		
1 centigram	=	0.01	=	0.154		
1 milligram	=	0.001	=	0.0154		

Here m and m^1 are the masses of the bodies, d is the distance between them, and a is a factor to be determined by experiment, called the gravitational constant.

74. Attraction Proportional to the Product of the Masses.—Since the force of attraction between two masses is directly proportional to the product of the masses, doubling the mass of one of the two bodies doubles the attraction, while doubling the mass of both bodies quadruples the attraction.

A man who can jump six feet high on the surface of the earth, if transferred to the surface of the moon, could jump thirty-six feet high, owing to the lesser attraction of the moon upon his body, while on the sun he could jump only two and one-half inches high, owing to the greater attraction of the sun.

75. Attraction Inversely Proportional to the Square of the Distance.—Doubling the distance between two bodies decreases the attractive force between them to one-fourth its former value; halving the distance between them increases its force to four times its former value.

The farther a body is carried above the earth's surface, the less the attraction which the earth has for it, and the less its weight. A body on the earth's surface is approximately four thousand miles from the earth's centre. If a pound weight could be carried four thousand miles above the earth's surface, it would weigh but one-quarter of a pound, since its distance from the earth's centre being doubled, the earth's attraction for it is diminished to one-fourth.

Since the earth is bulged out at the equator, a body at the equator is farther from the earth's centre than at the poles. The same body, therefore, would weigh more at the poles than at the equator; a man weighing $195\frac{1}{2}$ pounds at the equator would weigh $196\frac{1}{2}$ pounds at the poles.

If, however, we take a body below the surface of the earth, it would weigh less than at the surface, since the parts of the earth that are above it would pull in the opposite direction to the parts of the earth below it, and would, therefore, decrease its weight. At the centre of the earth a body would have no weight, since the attraction would be the same in all directions. For distances above the earth's surface the attraction is inversely proportional to the square of the distance from the centre of the earth.

$$W : w :: d^2 : D^2 \quad (10)$$

For distances below the surface of the earth the attraction is directly proportional to the distance from the centre of the earth.

$$W : w :: D : d. \quad (11)$$

In both formulas W is the weight of a body on the surface of the earth, and D its distance from the centre, while w and d are the corresponding quantities for the body above or below the surface.

The combined effect of mass and distance on the amount of attraction is seen in the tides of the ocean, which are caused by the attractions of the sun and moon. The mass of the sun is much greater than that of the moon, but since the moon is so much nearer the earth than the sun, the influence which the moon exerts in causing tides is much greater than that exerted by the sun.

In order to understand the effects of gravity, we must ascertain, as in the case of other forces—

(1) The direction in which it acts.
(2) Its point of application.
(3) Its intensity.

76. The Direction of Gravity.—Gravity acts in a vertical direction or approximately toward the earth's centre. A vertical line is perpendicular to a surface of water at rest.

The direction of gravity may be ascertained by the use of the plumb-line, which consists of a weight, W, Fig. 13, attached to the end of a string. If the other end of the string be held in the hand, when the weight has come to rest the string will be stretched in a vertical direction, and the plumb-line will point approximately toward the earth's centre.

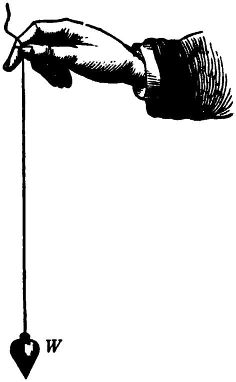

FIG. 13.—Plumb-line.

77. The Point of Application.—Centre of Gravity.—As gravity acts alike on all molecules in a body, there must be as many separate points of application as there are separate molecules.

The separate pulls, which may be regarded as so many separate components, may be replaced by a single resultant, equal to their sum, because they all act in the same direction, viz., vertically downward. This resultant pull is equal to the weight of the body, and its point of application is called the *centre of gravity*, because it is a point at which the whole weight of the body may be regarded as collected.

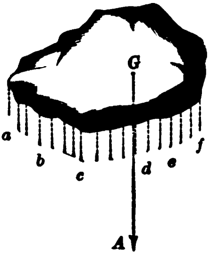

FIG. 14.

In Fig. 14 the vertical dotted lines *a*, *b*, *c*, *d*, *e*, *f*, etc., represent the separate pulls which gravity exerts on the molecules of the body. *G A* represents their resultant, and *G*, the point of application of this resultant, is called the centre of gravity of the body.

The centre of gravity of a body is independent of the position in which it is held, and whether the body is at rest or in motion.

78. Method of Determining the Centre of Gravity.—Suspend any body, such as a chair, by a string attached to any part, such as the top or the back, and allow the chair to come to rest. Observe the direction in which the string, if extended downward, would pass through the chair. The centre of gravity will be situated somewhere in this line, which is called the *line of direction of gravity*. Attach the string to some other part of the chair, such as one of the rungs; again suspend it, and observe, as before, the direction of the line extended downward along the string when the chair is at rest. The centre of gravity of the chair will be situated somewhere in this line. The centre of gravity is a point, and a point in order to be situated in each of two different lines must be at their intersection. The point, therefore, where these two lines intersect each other will be the centre of gravity of the chair.

Experiment 20.—Bore small holes at *a*, *b*, and *c*, in a rectangular plate of tin as shown in Fig. 15. Tie a string to the plate at *b*, and suspend the plate by the string, and, when it has come to rest, draw the line *b d* in the direction of the string extended. Then attach the string to some other point, as *c*, and, proceeding as before, draw the line *c e*. The centre of gravity of the plate will be found at *g*, where the line *b d* is cut by the line *c e*.

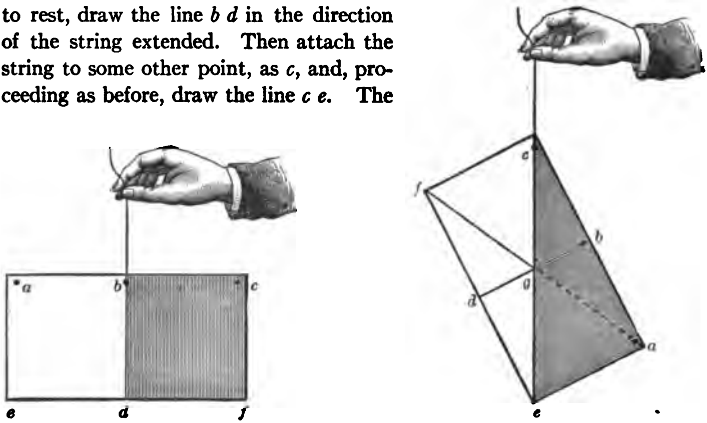

FIG. 15.—Method of finding the centre of gravity.

79. A Body Supported at Its Centre of Gravity Must be at Rest.—When, in Fig. 15, the plate of tin comes to rest in the position shown at the left, the shaded portion, *b c f d*, must be of the same weight as the unshaded portion, *a b d e;* for, were either of these portions heavier than the other, it would fall, and the line *d b* would take some other direction. So also the shaded portion *c e a* is of the same weight as the unshaded portion, *c e f*. The same is true of any other position in which the body comes to rest when suspended; the part of the body on one side of the line of direction is always equal in weight to that on the opposite side. A body at rest remains at rest when supported at its centre of gravity, because its weight is then equally distributed about its point of support.

80. Equilibrium of Bodies Supported on an Axis.—A body supported on a horizontal axis, around which it is free to turn, will be in equilibrium only when its point of support and its centre of gravity are in the same vertical line.

The point of support, in such cases, may have three different positions:

1. Above the centre of gravity.
2. Below the centre of gravity.
3. At the centre of gravity.

These three positions correspond to three different kinds of equilibrium; viz., *stable*, *unstable*, and *neutral equilibrium*.

81. Stable Equilibrium About an Axis.—Here the point of support is above the centre of gravity, and the body, when left to itself, again assumes a position of stable equilibrium.

Experiment 21.—Cut a disc from a flat piece of carboard and make a hole in it at *S*, with a needle, so as to allow the card to move freely around the needle. Hold the needle horizontally, as shown in Fig. 16. Observe that the card comes to rest in a position of stable equilibrium. Here the point of support *S* is above the centre of gravity *G*, and in the same vertical line with it (*SG*).

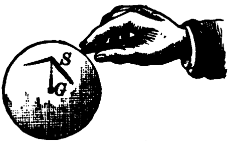

FIG. 16.

82. Unstable Equilibrium About an Axis.—Here the point of support is directly below the centre of gravity. Any motion of the body causes the centre of gravity to fall, and the body to assume a position of stable equilibrium.

Experiment 22.—Hold the pasteboard disc as shown in Fig. 17. Observe that it will be in a position of unstable equilibrium. Here the point of support, *S*, is directly below the centre of gravity, *G*, and is in the same vertical line with it. If the disc be slightly moved, the centre of gravity falls, and the disc assumes the position of stable equilibrium shown in Fig. 16.

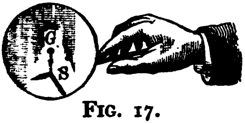

FIG. 17.

83. Neutral Equilibrium About an Axis.—Here the point of support coincides with the centre of gravity, and the body will remain at rest into whatever position it may be moved about the axis.

Experiment 23.—Hold the pasteboard disc as in Fig. 18. Observe that it will come to rest in a position of neutral equilibrium, and that no matter in what position the disc is set, it will remain at rest.

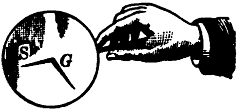

FIG. 18.

Here the point of support remains at the centre of gravity, no matter how the disc may be turned.

84. Equilibrium of Bodies Resting on a Flat Surface.—When a body has more than one point of support, as when some portion of the body is resting on a flat surface, it is not necessary that the centre of gravity be above any one of these points of support, in order that the body may be in equilibrium. It is sufficient if the vertical line passing through the centre of gravity, or the line of direction, falls within the base on which the body rests.

When the centre of gravity is as low as it can get, the body is in stable equilibrium. The lower the centre of gravity, and the greater the area of the base on which the body rests, the more stable the equilibrium. When the relative positions of the centre of gravity and the point of support remain the same in any position of a body, the body is in neutral equilibrium.

A book placed as at *A*, Fig. 19, will be in stable equilibrium, since it is resting on a large base, and its centre of gravity is as low as it can get.

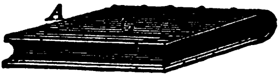

FIG. 19.

In order to overturn the book from this position its centre of gravity must be raised until the vertical line passing through it falls outside the base.

When standing as at *B*, Fig. 20, the book will still be in stable equilibrium; but since the base on which it rests is smaller than when placed as at *A*, its centre of gravity is higher, and the equilibrium is less stable than at *A*; *i. e.*, a slight push will bring the centre of gravity over the base and overturn it.

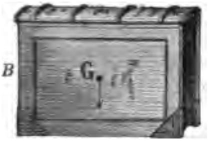

FIG. 20.

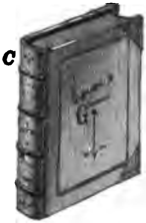

FIG. 21.

When placed as at *C*, Fig. 21, the equilibrium, though still stable, will be less stable than at *B*, since the base on which the book rests is still smaller and the centre of gravity higher.

A sphere, resting on a level table, is in neutral equilibrium, because no movement can change the relative positions of its centre of gravity and its point of support; the centre of gravity being at the centre of the sphere, and the point of support immediately beneath.

In a boat loaded with people the equilibrium is more stable if the passengers remain seated than if they stand up, because, when they stand up, the centre of gravity is raised, and the boat, if small, may upset.

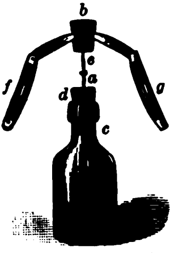

FIG. 22.—Experiment in stable equilibrium.

Experiment 24.—Fasten a stout pin, *a*, upright in a cork, *d*, placed in the mouth of a narrow bottle, *c*, Fig. 22. Stick the blunt end of a stout needle, *e*, in a cork, *b*, on the sides of which two penknives, *f* and *g*, are placed as shown. Carefully place the point of the needle on the head of the pin, and observe that it will not only rest there in a position of moderately stable equilibrium, but that the cork and knives may even be moved around without falling. As the head of the pin is generally more or less rounded, it should be rubbed flat with a file.

The centre of gravity may be situated outside a body, as in the case of a ring, where the centre of gravity is at the centre of the ring.

85. The Laws of Falling Bodies.—The laws of falling bodies were discovered by Galileo, an Italian philosopher. They may be expressed briefly as follows:

First Law.—The acceleration of a falling body is independent of its mass.

Gravity acts on each molecule of the body; if the molecules were all separated, each would fall to the earth with the same acceleration, because the same force acts on each. Their being united in one mass makes no difference, since gravity acts on each molecule as though it were alone. The number of molecules in any body, or in its mass, therefore, has no effect on its acceleration.

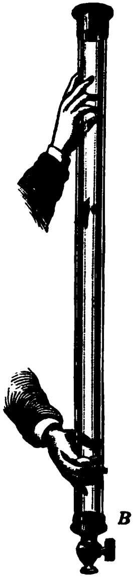

FIG. 23.—Bodies falling through an empty space.

Should we yoke together two equally fast horses abreast, so as to give them perfect freedom of motion, the two together would not be able to run any faster than either separately. It is the same with the motion of molecules toward the earth.

Second Law.—The acceleration of a falling body is independent of the shape or nature of the body.

So far as our every-day experience goes, this law would appear to be incorrect, since a piece of gold in the shape of a ball will fall more rapidly through the air than when beaten out into gold-leaf; again, a small piece of cork falls less rapidly through the air than a piece of iron of the same size.

It is the resistance of the air which causes these apparent exceptions to the law. In a vacuum or empty space all bodies, whatever their size, shape, or material, fall with the same acceleration; a feather and a leaden bullet, for example, let fall from the same height, at the same time, would reach the bottom of the empty or exhausted vessel *B*, Fig. 23, at the same instant.

Experiment 25.—Let two iron weights, one weighing, say, an ounce, and the other weighing a pound, fall from the hand at the same time. Observe that the eye is unable to detect any difference in the time of falling.

Third Law.—The velocity acquired, at the end of any given time, by a body falling freely from a state of rest is proportional to the time during which it has been falling.

Thus, a body falling freely from a state of rest in a vacuum in the latitude of Washington, D. C., would have a velocity at the end of the first second equal to about 32.16 feet per second, or 980.1 cm. per second.

The velocity at the end of the second second is 32.16 × 2 = 64.32 feet per second. The velocity at the end of the third second is 32.16 × 3 = 96.48 feet per second, and so on. Here the velocity increases as the time and is proportional to the numbers 1, 2, 3, etc. The quantity 980.1 cm. per second is called the *acceleration of gravity.* This acceleration varies at different parts of the earth's surface, being least at the equator, where it is 978.1, and increasing with the latitude to a maximum at the pole, where it is supposed to be 983.1. Let g represent the acceleration of gravity, then

$$v = g\,t. \quad (12)$$

Fourth Law.—The distances fallen through in successive seconds increase as the odd numbers, 1, 3, 5, 7, etc.

A body falling freely from a state of rest passes through 16.08 feet during the first second of its descent. But the velocity of any falling body is constantly increasing, since gravity is constantly imparting an impulse to the body, which is added to the velocity already acquired.

During the second second it falls through three times 16.08 feet, or 48.24 feet; during the third second, it passes through five times 16.08 feet, or 80.40 feet, etc. Let s represent space in one second, then

$$s = \tfrac{1}{2}\,g\,(2\,t - 1). \quad (13)$$

Fifth Law.—The total distance in feet through which a body will have fallen freely in a given time is proportional to the square of the time, and is equal to the square of the time in seconds multiplied by 16.08.

Thus, a falling body falls four times as far in two seconds as in one second, and nine times as far in three seconds as in one second.

During the first second the body falls through 16.08 ft.; during the second second it falls through 48.24 ft.; at the end of the second second it has fallen through a total distance of 48.24 + 16.08 = 64.32 ft. But 64.32 is four times as great as 16.08; that is, at the end of the second second the body has fallen through a space 2 × 2, or 2 squared, greater than what it fell during the first second, or, in other words, the whole space fallen through is proportional to the square of the time.

$$\text{Here } S = \tfrac{1}{2} g t^2. \quad (14)$$

The actual values for the latitude of Washington, D. C., are given below.[1]

86. Atwood's Machine.—The velocity acquired by a falling body is too great to permit the direct experimental verification of the third, fourth, and fifth laws, even if the resistance of the air did not interfere with the result. Various apparatus have, therefore, been constructed to permit such experimental verification. Atwood's machine and Galileo's inclined plane are examples of such apparatus.

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[1] Number of seconds.	Distances fallen through during particular seconds.		Total distances fallen through at the end of any number of seconds.	
1	16.08 feet	490.04 cm.	16.08 feet	490.04 cm.
2	48.24 “	1470.12 “	64.32 “	1960.16 “
3	80.40 “	2450.20 “	144.72 “	4410.36 “
4	112.56 “	3430.28 “	257.28 “	7840.64 “
5	144.72 “	4410.36 “	402.00 “	12261.00 “
6	176.88 “	5390.44 “	578.88 “	17641.44 “

In Atwood's machine (Fig. 24) two equal weights are hung by a light cord passing over a pulley, the friction being made as small as possible. In the form illustrated this is done by means of agate bearings for the steel spindle. As the weights are equal, no motion takes place. If now a small excess is added to one weight, this one will fall while the other rises. Since the mass to be moved is large, while the moving force is small, the acceleration will be small. If each weight is at first 88 grams and the added weight is 4 grams, the total mass to be moved will be 180 grams, while the moving force will be but 4 grams weight. The acceleration will, therefore, be but $\frac{4}{180}$ or $\frac{1}{45}$ of that of a freely falling body.

A perforated platform may be used to remove the excess weight after it has acted for any given time, so that uniform motion may be studied with this machine, as well as accelerated motion.

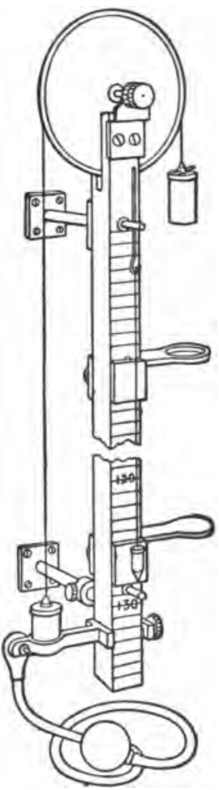

Fig. 24.—Atwood's machine.

87. Galileo's Inclined Plane.—A body rolling down an inclined plane, although it moves with a uniformly accelerated velocity, like a falling body, yet moves less rapidly. Galileo adopted this device for observing the rate of fall. He caused a heavy ball to roll down an inclined plane, the length of which was so proportioned to its height as to permit the motion of the ball to be readily followed by the eye.

By means of Atwood's machine or of an inclined plane the distances which a body falls for any number of seconds may be found. If these results are tabulated, they will be as follows:

Time in seconds.	Space passed over during each second.	Velocity at the end of each second.	Whole space passed over.
1	d	$2d$	d
2	$3d$	$4d$	$4d$
3	$5d$	$6d$	$9d$
4	$7d$	$8d$	$16d$

If a body moves with uniform acceleration, the distance d, passed over in the first second, is equal to one-half the acceleration. Therefore, $d = \frac{1}{2}a$. Substituting this value in the above table, we have—

1	$1 \times \frac{1}{2}a$	a	$1 \times \frac{1}{2}a$
2	$3 \times \frac{1}{2}a$	$2a$	$4 \times \frac{1}{2}a$
3	$5 \times \frac{1}{2}a$	$3a$	$9 \times \frac{1}{2}a$
4	$7 \times \frac{1}{2}a$	$4a$	$16 \times \frac{1}{2}a$
t	$s = \frac{1}{2}a(2t-1)$	$v = at$	$S = \frac{1}{2}at^2$

By this means the above formulas for accelerated motion may all be derived from the experimental data. If the results of this last table are drawn to scale, we have this drawing, Fig. 25, which may be called the *graphical analysis* of a falling body.

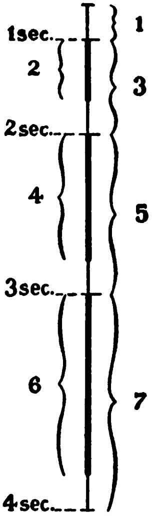

Fig. 25.

The light lines represent the uniform acceleration due to the constant attraction of the earth. The heavy lines represent the velocity acquired by the body during the different portions of its fall.

88. Projectiles.—Projectiles are bodies thrown through the air. They are acted on—

(1) By a momentary force which gives the projectile a uniform velocity.

(2) By the constant force of gravity which gives it a constant acceleration.

(3) By the resistance of the air.

A projectile thrown vertically upward must move with a constantly retarded velocity, since gravity is constantly acting upon it. Eventually, the projectile stops moving upward and begins to descend. Disregarding the resistance of the air, the projectile, at any point in its descent, will have the same velocity it had at that point in its ascent, and will reach the point from which it was thrown with the velocity it had when it began to rise.

When projected vertically upward, the path of a projectile is a straight line; in any other direction its path is a curve.

Suppose, for example, a projectile be thrown in a horizontal direction *F H*, Fig. 26, with a velocity that would carry it through the equal spaces *Fa*, *ab*, *bc*, *cd*, and *d H*, during the 1st, 2d, 3d, 4th, and 5th seconds. Gravity is constantly acting, and during these five seconds the body would fall through the spaces, 1, 3, 5, 7, and 9 respectively. By the constant action of gravity on the projectile's motion the body would be at *A*, *B*, *C*, *D*, and *E*, at the end of 1, 2, 3, 4, and 5 seconds respectively, and would, therefore, move through the curved path, *F A B C D E*.

89. Range.—A body projected horizontally will strike the ground at a horizontal distance from its starting-point, which, disregarding the resistance of the air, is equal to the distance it would have gone during the time of falling, with the velocity originally given by the projecting force. This horizontal dis-

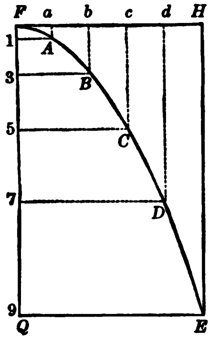

FIG. 26.

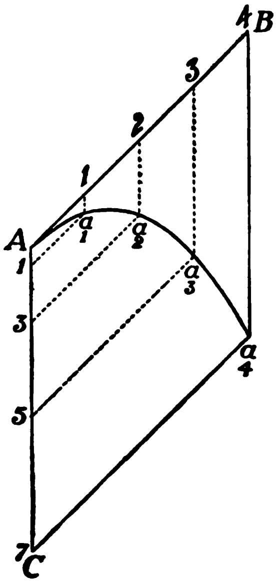

FIG. 27.

tance is called the *range*. Thus, in Fig. 26, the body projected horizontally at F, toward H, strikes the ground at E; the distance $Q\ E$ is, therefore, its range.

If the body be projected upward in any other direction than vertically, its horizontal range will depend upon the angle of elevation, as well as upon the velocity.

The path of a body projected upward may be found as follows: Let the line AB (Fig. 27) represent the direction in which the body is projected. Lay off on this line equal spaces to represent the uniform velocity given to the body by the impulsive action of the projecting force. On the line Ac lay off the distance passed over by a freely falling body in each second. By the parallelogram of velocities we then find the position of the body at the end of each second, and connecting these by the curved line $A\ a_1, a_2, a_3, a_4$, we have the path of the projectile.

90. Ballistic Curve.—Were there no resistance offered by the air to a projectile, its path would be the curve called a parabola. But, in consequence of this resistance its actual path through the air is in a very different curve called a ***ballistic curve*** (Fig. 28).

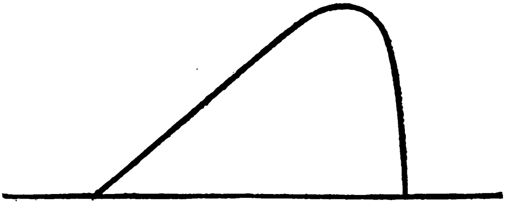

FIG. 28.

The vertical distance attained by the projectile, as well as its range, is diminished by the resistance of the air.

For this reason the actual range of any projectile, fired from a gun, is much shorter than its range calculated as in Section 89 for unretarded velocity.

91. The Pendulum.—A pendulum consists of a mass, *b*, Fig. 29, suspended by a string or rod *a b*, from a fixed support *a*, about which it is free to move. The mass *b* is called the *bob* of the pendulum. When the pendulum is at rest, the bob and its supporting string assume the position of the vertical *a b*. If, now, the bob be raised so as to assume the position shown at *a c*, it will, when allowed to fall, move toward its old position *a b*, along the curved line *c b*. When, however, the position *a b* is reached, the pendulum does not cease moving; for the momentum it has acquired in falling from *c* to *b*, carries it past this position to *d*. When the pendulum reaches *d*, it again falls toward *b*, and acquires momentum sufficient to carry it to *c*, and so on, continuing to swing to-and-fro between *c* and *d*. Each complete swing from *c* to *d* and back again from *d* to *c*, is called a *vibration* or *oscillation*. The half vibration from *c* to *d* or from *d* to *c* is called a *beat*. The time it takes the pendulum to move through each complete swing is called the *time* or *duration of an oscillation*. The curved line *b c*, or *b d*, which marks the distance the pendulum has been moved from the vertical *a b*, is called the *amplitude of the oscillation*.

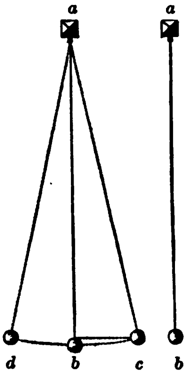

FIG. 29.

92. The Laws of the Pendulum.—*First Law.—In the same pendulum, if the amplitude of the oscillation is small, the time of oscillation for different amplitudes is nearly the same.*

Vibrations that are performed in equal times are called *isochronous*. This law is sometimes called the *law of isochronism of the pendulum*.

Galileo first discovered this law by watching the motions of a lamp swinging at the end of a long chain suspended from the cathedral roof at Pisa.

Unless the pendulum is connected with a spring or weight, the resistance which the air offers to its movement will cause it to swing through smaller and smaller arcs until it finally comes to rest.

Second Law.—In pendulums of different lengths the time of oscillation is directly proportional to the square roots of the lengths.

Experiment 26.—Attach a plumb bob to a short string of a given length, and count the number of oscillations it makes in a given time. Attach another plumb bob to a string nine times as long as the first: it will complete but one oscillation in the time the other completes three oscillations. Since the lengths of the two pendulums are as 1 is to 9, and their oscillations are as 1 is to 3, it is evident that in pendulums of different lengths the time of their oscillations is directly proportional to the square root of their length.

In the latitude of Washington, a pendulum to beat seconds must be about 39.1 inches in length or nearly one metre.

93. The Intensity of Gravity.—The force with which gravity acts at any place, on any given mass of matter, may be ascertained by the weight of that mass. This, however, varies in different latitudes, being greater at the poles than at the equator. A man weighing 195½ lbs. at the equator, would weigh 196½ lbs. at the north or south pole.

The time of oscillation of a pendulum is inversely proportional to the square root of the intensity of gravity. Consequently, if we could shift a pendulum to some planet where gravity was four times stronger, the pendulum would oscillate twice as fast and the time of oscillation would be one-half as great.

Since gravity is the cause of the motion of the pendulum, we can determine the variations in the intensity of gravity at different parts of the earth by counting the number of oscillations the pendulum makes in a given time. If we carried the same pendulum from the equator toward the pole, we should find that the number of its oscillations would increase gradually, thus showing that the force of gravity was becoming greater and greater. We can illustrate this by placing a magnetic needle near a bar magnet. When at a distance, it will oscillate slowly. As we decrease the distance, the time of oscillation decreases and it oscillates more rapidly.

The laws of the pendulum are expressed by the formula

$$t = 2\pi\sqrt{\frac{l}{g}}. \quad (15)$$

That is, the time of vibration for small arcs is independent of the arc, since this term does not enter into the formula.

The time of vibration is directly proportional to the square root of the length.

The time of vibration is inversely proportional to the square root of the attraction of gravity.

94. Variations in the Force of Gravity.—The force of gravity varies at different parts of the earth's surface:

1. On account of the shape of the earth, which is approximately an oblate spheroid.

A place on the earth's surface at the equator being at a greater distance from the earth's center than a place on the surface at the poles, the intensity of gravity will be less at the equator than at the poles.

2. On account of the earth's rotation on its axis.

The centrifugal force arising from the earth's rotation is greatest at the equator and nothing at the poles. Therefore, the apparent force of gravity varies with the latitude.

Consequently, if the earth were at rest and were a uniform spherical globe, gravity would have uniform intensity all over its surface.

PROBLEMS

1. A man weighs 150 lbs. avoirdupois. Express his weight in kilograms.

2. What is the weight, expressed in grams, of 200 cubic centimetres of distilled water at the temperature of its maximum density (4° C.)?

3. If a boy weighs 80 lbs. avoirdupois upon a spring balance at the equator, what would be his weight, with the same spring balance, if he could be weighed at the north or the south pole?

4. Assuming the earth to be a sphere 4000 miles in radius, what would the boy weigh by the spring balance at an elevation of 100 miles above the level of the sea?

5. What will be the velocity of a freely falling body at the end of the fourth second? How far will such a body move in the 4 seconds? How far during the 4th second?

6. A cannon ball is fired from the top of a vertical cliff 900 ft. high, with a horizontal velocity of 1000 ft. per second. (*a*) How soon will it strike the level plain? (*b*) How far from a point directly beneath the cannon will it strike?

7. A body shot from the top of a cliff with a horizontal velocity of 400 ft. per second strikes the ground at a horizontal distance of 2000 ft. from its starting-point. How high is the cliff?

8. A ball is thrown vertically upward with a velocity of 100 ft. per second from a balloon which is sinking at the rate of 40 ft. per second. How far will the balloon be from the ball at the instant that the ball begins to fall?

9. What is the length of a pendulum which will beat 4 times in 3 seconds?

10. Find the length of a seconds pendulum at the poles. $g = 32.25$.

11. What will be the value of g at a place where a pendulum 39.1 in. long beats seconds?

12. The attraction of two bodies for a third are as 3 : 4 and their masses as 3 : 8. What are their relative distances?

13. If the distance between two bodies is increased four-fold, how much greater must the product of their masses be to keep their mutual attraction the same?

CHAPTER VI

COHESION AND ADHESION, AND PROPERTIES PECULIAR TO SOLIDS

95. The Force of Molecular Attraction.—The force by which molecules either of the same or of different kinds of substances are held together is called the force of molecular attraction.

It is convenient to speak of the molecules as being held together by the *force of molecular attraction*. By this expression is meant the fact that they are held or constrained by the force of attraction to maintain a certain average distance apart during their to-and-fro movements.

The cause of molecular attraction is unknown. Molecular repulsion, which prevents the molecules from coming together, appears to be due to heat energy.

Cohesion is the name given to the force of molecular attraction when it holds together molecules of the same kind of substance. *Adhesion* is the name given to this force when it holds together molecules of different kinds of substances.

96. Cohesion varies greatly in different substances; in some, such as iron or steel, it is very great; in others, such as butter or putty, it is quite feeble. It is the cohesion of a solid that causes it to retain its shape.

The force of cohesive attraction appears to act only at very small distances. If we overcome the cohesion between the molecules of a piece of iron or china, we cannot cause their molecular attraction again to bind them by merely pressing the broken edges together. It would appear as if we could not thus bring enough of the molecules sufficiently near to one another.

In the process of *welding* metallic substances the ends that are to be connected in the welded joint are brought to a heat sufficient to soften them and are then pressed or hammered, thus causing them to cohere strongly together. In electric welding the welding temperature is obtained by passing a strong electric current through the pieces of metal that are to be joined.

Dry, powdered graphite, when thoroughly cleansed, may, by great pressure, be consolidated into a coherent mass that may readily be cut into strips for use as lead pencils.

Two fresh surfaces of lead may be made to cohere with considerable force by merely pressing them together.

Experiment 27.—Cast a cylinder of lead about one inch in length and a quarter of an inch in diameter. This can be done by boring a hole of the proper size in a piece of hard, dry wood, and pouring molten lead into the hole. This is a dangerous operation if the wood is damp, as an explosive scattering of lead may occur. Cut the cylinder in half by resting a sharp knife against its side and striking the knife a few blows with a hammer. Attach strings or wires to the ends of the pieces, as shown in Fig. 30. Press the freshly cut surfaces firmly together, being careful not to touch them; observe that they will cohere with sufficient force to sustain a heavy weight placed below, on a pan made by tying strings to the four corners of a piece of stout cardboard.

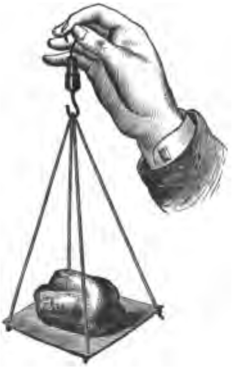

FIG. 30.—Cohesion of lead.

97. Cohesion of Liquids.

—The molecules of liquid substances move over one another so easily that we might suppose they possessed no cohesion. They do, however, exert a cohesive attraction for one another, though this attraction is much less than in solids.

Had liquids no cohesion, the drops of dew on foliage would be flattened by gravity into thin layers, instead of assuming an almost spherical shape. The intensity of the force of cohesion varies in different liquids.

When a pipe bowl is dipped into soapy water, the cohesion of the liquid is shown by the film which remains stretched over the surface of the bowl.

98. Adhesion.—When the force of molecular attraction acts on the molecules of different kinds of matter, we call the force *adhesive* attraction, to distinguish it from *cohesive* attraction. Thus, the hand, when dipped in water, is wet; here we say the water adheres to the hand, because the attraction is exerted between different kinds of molecules; namely, between those of the hand and those of the water. Chalk-marks adhere to a blackboard, but the molecules of chalk cohere to one another.

99. Adhesion between Solids.—The resistance to motion, produced by friction, is caused not only by the irregularities of the surfaces, but also by the molecular attraction which such surfaces exert on one another.

Cements afford examples of adhesion between different kinds of solids. Thus, mortar adheres to stones or bricks and so binds them together. Glue adheres to the pieces of wood or cloth between which it is placed. Paste or gum causes paper to adhere to walls. Dried paint adheres to wood-work, and ink-marks to paper.

100. Adhesion between Solids and Liquids.—1. *Wetting.*—When plunged into water, the hand becomes wet, because the water adheres to it; but if plunged into mercury, the hand is not wet, because there is but little adhesion between it and the mercury. Water-proof fabrics contain substances that are not readily wet by water. When rain falls on such fabrics, it either falls off, or can be easily shaken off.

2. *Solution.*—When a lump of sugar is thrown into a glass of water, the sugar gradually disappears and becomes mixed throughout the liquid, which acquires a sweet taste. We call this change *solution.* By solution a solid becomes changed into a liquid.

The solvent power of water is much greater than that of nearly any other common liquid. As a rule, the solvent power of any substance increases with the temperature; thus, hot water will dissolve more sugar than cold water. This, however, is not always the case; cold water will dissolve more lime than hot water.

101. Capillarity.—If a tube *A*, Fig. 31, of large diameter, be dipped into a liquid which wets it, the liquid will stand about as high outside of the tube as inside; but if the tube be of smaller diameter, as at *B*, and the liquid wets the tube, it will rise higher inside the tube than outside of it. If the tube be still smaller, as at *C*, the liquid will rise higher than at *B*. The surface of the liquid in all the tubes will be concave, as shown in the figure.

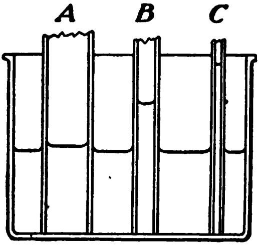

FIG. 31.

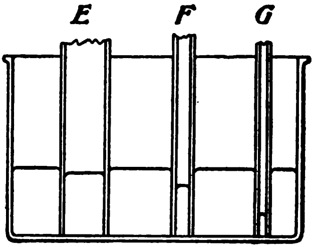

FIG. 32.

When the liquid does not wet the walls of the tube, if the tube be of large diameter, as shown at *E*, Fig. 32, the level inside is about the same as that outside; but if the diameter be small, as at *F*, the liquid will be depressed within the tube, so that the level on the inside of the tube will be lower than that on the outside, and the free surface of the liquid will be convex. In a tube of still smaller diameter, as at *G*, the depression will be greater than at *F*. These phenomena are called *capillary* phenomena. A *capillary tube* is one whose diameter is small or hair-like.

Capillarity deals with the elevation or depression of liquids in tubes of small diameter.

The principal phenomena of capillarity are:

(1) A liquid rises in a capillary tube when it wets the tube and has a concave surface, but is depressed when it does not wet the tube and has a convex surface.

(2) The amount of the elevation or depression is greater as the diameter of the tube decreases.

(3) The amount of elevation or depression varies with the kind of liquid and with the temperature.

102. Surface Tension.—Below the surface of a liquid mass, the molecules being attracted in all directions by the surrounding molecules, possess great freedom of motion. At the surface of a liquid, however, the molecules, being attracted only by the molecules below them, have comparatively little freedom of motion, the liquid acting as though a thin skin or film was stretched over its surface. The tension so produced at the surface of a liquid is called *surface tension.*

The surface tension on the liquid contained within the film tends to reduce the contained liquid to the shape in which its free surface shall have the least area; *i. e.*, the spherical shape. This is the reason a soap-bubble assumes a spherical form; or the drop of melted lead, allowed to fall from a shot tower, assumes the spherical form of shot, or that a drop of oil, when placed in a mixture of alcohol and water of the same density, assumes a spherical shape.

Experiment 28.—Blow a soap-bubble by means of a pipe in the usual manner. Observe that though the bubble may not be truly spherical while being blown, yet as soon as the blowing ceases, its surface tension causes it to assume a spherical shape.

103. The Cause of Capillary Phenomena.—Capillary phenomena result from the difference between the cohesion of the liquid molecules for one another, and their adhesion to the walls of the capillary tube.

Capillary phenomena may be regarded as due to surface tension, modified by the adhesion of the liquid to the walls of the tube; since, however, surface tension is the result of cohesion, the phenomena of capillarity result from the cohesion of the molecules of a liquid to one another and their adhesion to the walls of the capillary tube.

A liquid rises in a capillary tube which it wets, because the adhesion between the liquid and the walls of the tube draws the liquid toward the walls of the tube. A liquid is depressed in a capillary tube which it does not wet, because the cohesion of the liquid draws it away from the walls of the tube. If the liquid wets the tube, the adhesion between it and the tube, or the force which draws the liquid toward the walls, is greater than the force of cohesion, which tends to keep the particles of the liquid together. If the liquid does not wet the tube, the force of cohesion is greater than that of adhesion.

104. Familiar Examples of Capillarity.—The phenomena of capillarity occur in loose, porous substances, whenever the spaces, or sensible pores, between the particles are of capillary dimensions. Thus oil rises in the wick of a lamp, through the capillarity of the spaces between the strands. A lump of sugar, placed with only its lower end in milk or water, is soon wet throughout; here the elevation of the liquid is due to capillarity. A towel, hung so that only its lower end dips in water, is soon wet for a considerable distance above the level of the water, from the same cause.

105. Osmose is the unequal mixing of two different liquids through the pores of a membranous substance which separates them.

Two liquids, capable of mixing with each other, placed in compartments of the same vessel, separated only by a thin wall of bladder, or other suitable membrane, through the pores of which the liquids can pass slowly, will not remain separate, but will mix with each other. This mixing, however, is different, from that produced by mere diffusion. If, for example, sugar and water be placed in one compartment, and pure water in the other, it will be found that more of the pure water will pass into the compartment containing the sugar and water than will the sugar and water into the other compartment. After standing for several hours, therefore, the level of the liquid will be higher in the compartment containing the sugar and water.

Experiment 29.—Osmotic flow is easily shown by the use of a diffusion thimble of parchment paper attached to the end of a piece of barometer tubing provided with a funnel and stop-cock, as shown in the illustration. It is necessary that the thimble should be very firmly fastened by thread and wax. A strong sugar solution, colored by some dye, is poured in through the funnel and the thimble immersed in water. In a short time the colored liquid rises in the tube to a very considerable height, and in time some dye will be evident in the outer vessel. This action is called osmosis, and the pressure required to hold up the sugar solution in the tube is called osmotic pressure.

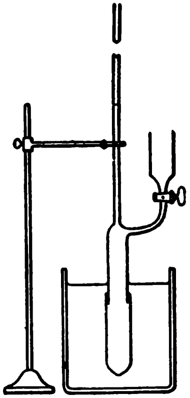

FIG. 33.—Osmose.

The explanation required, as suggested by Watson, appears very simple. The parchment is struck on both sides by water molecules, but on the inside there are fewer of these molecules in unit volume, as some space is occupied by the sugar molecules which cannot so readily pass through the membrane. Therefore, the water molecules pass into the tube until the pressure of the column of water balances the osmotic pressure.

Osmose may be very strikingly shown by means of a carrot. Peel the carrot, bore a hole in the centre, fill this with a concentrated sugar solution, and put in the hole a close-fitting cork, through which a glass tube passes. Immerse the carrot in water until the cork is covered. In a few hours osmotic pressure will have caused the water to rise in the tube to a very considerable height.

106. Dialysis.—Substances differ in their power of passing through a membranous wall. Crystallizable substances, or *crystalloids*, such as sugar and common salt, as a rule, pass freely through such a wall; while uncrystallizable substances, or *colloids*, such as gums, glues, or jellies, do not pass at all.

Graham, a distinguished chemist, based on this fact a process called *dialysis*, for the separation of crystalloids from colloids. A mixture of the colloids and crystalloids to be separated was placed in the *dialyzer*, consisting of a vessel the bottom of which is formed of a sheet of artificial parchment paper floated in a vessel of pure water. In a few days the crystalloid substances had passed through the dialyzer into the water, while the colloids had remained in the dialyzer. Arsenious acid, a crystalline substance, may be separated in this way from substances containing it. This process is, therefore, used to detect the presence of arsenic in cases of suspected poisoning.

107. Adhesion between Solids and Gases.—Adhesion between solids and gases is seen in the *absorption* of gases by solids. Charcoal has a wonderful power of absorbing various gases and condensing them within its pores. Freshly burned charcoal can absorb nearly a hundred times its own bulk of some gases. When thrown on decaying animal or vegetable substances, it removes most of their bad odors by absorbing the malodorous gases as fast as they are given off.

108. Adhesion between Liquids and Gases.—Most liquids have the power of absorbing various gases. Water possesses this property in a remarkable degree.

Experiment 30.—Place a few drops of aqua ammonia in a test-tube and apply heat until it begins to boil. Quickly invert the tube in a tumbler of water. Observe that the water rises in the test-tube as the ammonia vapor is absorbed by the water.

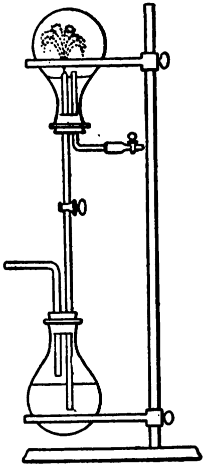

FIG. 34.

A pleasing variation of this experiment is the ammonia fountain. Strong ammonia water is boiled in a flask and the gas is allowed to fill an inverted round-bottomed flask by air displacement. The flask is provided with a two-holed stopper, through one hole of which passes a glass tube drawn out to a small opening, while through the other opening is a right-angled tube of glass. When the flask is filled with ammonia, the lower end of the jet tube is placed in a flask of water and the other tube closed. The gas is absorbed by the water, which reduces the pressure in the flask, and the atmospheric pressure, therefore, forces the water up in the form of a fountain. If the lower flask is also provided with a two-holed cork, as shown in the illustration, the fountain may be more quickly started by blowing into the side tube.

All water which has been exposed for some time to the air will be found to contain a considerable amount of air in solution. If a tumbler of clear water be allowed to stand for some time, minute bubbles of gas will collect on the inside of the glass. These bubbles come from the air which was dissolved in the water.

If a tumbler of water be placed under the receiver of an air-pump and a vacuum be made in the receiver, the air in the water will escape in a stream of bubbles.

109. **Properties Peculiar to Solids.**—The solid condition of matter is characterized by certain properties peculiar to it. The most important properties peculiar to solids are malleability, ductility, hardness, brittleness, tenacity, elasticity of flexure or torsion, and crystalline form.

110. **Malleability** is the property certain solids possess of being wrought into different shapes under the hammer or roller. The molecules of malleable bodies possess the power of flowing or moving over one another under the hammer or roller. Most of the metals are malleable to a certain extent, and on this property much of their value depends. Gold is the most malleable metal known. It can be beaten into leaves so thin that it takes 300,000 such leaves to make a pile one inch in thickness. The malleability of metals under the hammer is somewhat different than under the roller. Gold, lead, silver, tin, and copper are very malleable.

111. **Ductility** is the property certain solids possess of being drawn out into wire. This property is possessed generally by the metals, and is nearly the same as malleability, since in both the molecules of the body, when subjected to pressure or strain, are caused to flow or move over one another without fracture

occurring in the metal. The different metals, however, are not malleable and ductile to the same extent.

Platinum, silver, iron, and copper are very ductile.

112. Hardness is that property by which certain substances resist being scratched or worn by others. We can tell which of two substances is the harder by rubbing them together; that which is the harder will scratch the other. The terms *hard* and *soft* are relative, since a body which is hard, when compared with one substance, may be soft when compared with another; thus, glass will scratch marble; therefore, glass is hard when compared with marble, but the diamond will scratch glass, so that glass is soft when compared with the diamond.

A scale of hardness is made by arranging a number of mineral substances in such an order that each is readily scratched by any mineral following it, but itself scratches any which precedes it. Such a table is as follows:

1. Green laminated talc.
2. Crystallized gypsum.
3. Transparent calc spar.
4. Crystalline fluorspar.
5. Transparent apatite.
6. Cleavable feldspar.
7. Transparent quartz.
8. Transparent topaz.
9. Cleavable sapphire.
10. Diamond.

This table is used as follows: Flint scratches quartz with difficulty, but is readily scratched by topaz. Its hardness is, therefore, taken arbitrarily as, say, 7.5, or of intermediate hardness between topaz and quartz.

In the *sand-blast process* a stream of fine sand, driven by a jet of air or steam, is used to cut designs on glass, or to cut through hard metals.

113. Hardening, Annealing, Tempering.—Certain metals possess the property of having their hardness changed by heat. If they are heated about to redness, and then suddenly cooled by being plunged into cold water, they become hard and brittle. Steel possesses this property in a remarkable degree. The process is called *hardening*.

When steel is highly heated and allowed to cool slowly, it becomes soft, ductile, and malleable. This process is sometimes called *softening* or *annealing*.

Investigation by chemical and microscopical methods has shown that the properties acquired by steel when hardened or annealed are due to the formation of definite chemical compounds.

If a bar of hardened steel is struck a sharp blow with a hammer, it is apt to be fractured; but if softened, it may be wrought into any desired form, such as a knife-blade, an ax, or a hatchet, and these articles may afterward be hardened by high heating and subsequent rapid cooling. As a rule, the hardness so obtained is so great that the articles would be too brittle for use; in this case a portion of the hardness may be removed by heating to a lower temperature, and then allowing them to cool. This process is called *tempering*.

114. Brittleness.—A substance is brittle when it is readily broken into pieces. This property is almost the opposite to that of malleability. Brittle substances are generally hard.

115. Tenacity.—By the tenacity of a substance is meant its power to resist being pulled apart. The tenacity of a body is due to the cohesion of its molecules, and, as cohesive attraction varies greatly in different substances, the tenacity must also vary.

If the force tending to pull the molecules apart is applied in the direction of the length of the body, the tenacity must increase with the area of transverse section, that is, a section made at right angles to the length; for, if of the two bars, *A* and *B*, Figs. 35 and 36, of the same material, *A*, has a smaller area of transverse section, *a b c d*, than *e f g h*, of *B*, then the total tenacity of *A* must be less than that of *B*, since there are fewer molecules in any cross-

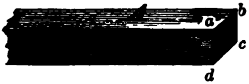

FIG. 35.

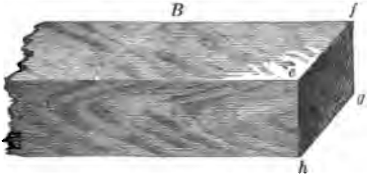

FIG. 36.

section of *A* tending to hold the bar together than there are in any cross-section of the larger bar *B*. If, then, the area *e f g h* be four times as great as *a b c d*, the bar *B* would require four times as great a force to pull it apart as the bar *A*, and so also with any other proportion of areas.

The tenacity of a bar or beam is independent of its length. The increase in the length does not affect the number of molecules in any area of cross-section; but the greater the length of the beam, the greater the probability of a flaw or a weak spot, so that a long beam is likely to have less tenacity than a short beam, and would, of course, break at its weakest part. Since, however, the weight of the beam tends to break it, we can see that the breaking weight is less as its length increases.[1]

116. Measurement of Tenacity.—The tenacity of a body is measured by finding the force required to pull it apart. This is technically known as the *breaking weight*. An instrument used for this purpose, when the breaking strength of wire is to be found, is shown in Fig. 37. The diameter of the wire is first

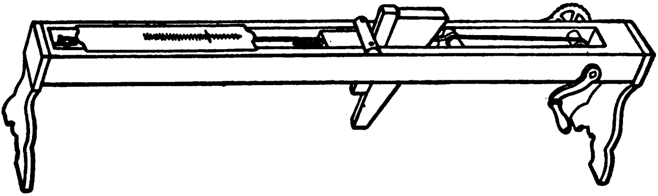

FIG. 37.—Wire-breaking machine.

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[1] **Table of Tenacity (per Unit of Cross-section)**

	Lbs. per sq. in.	Kilograms per sq. centimetre.
Wrought iron	50,000	3500
Cast iron	20,000	1400
Structural steel	60,000	4200
Special steel	100,000	7000
Concrete	300	21
Timber	10,000	700

measured by a micrometer caliper, Fig. 38; this has a movable jaw the screw head of which records to the hundredths of a millimetre. The wire is then placed in the machine, one end fastened to the spring balance, and the other end to the axle. This is then turned slowly until the wire breaks, the recoil being prevented by wedges or clamps. The spring balance will then record the breaking weight of that piece of wire. To compare different substances with each other it is necessary to find the *coefficient of tenacity* of each. By this term is meant the breaking strength of unit cross-section, that is, the number of kilograms required to break a wire of one square centimetre cross-section.

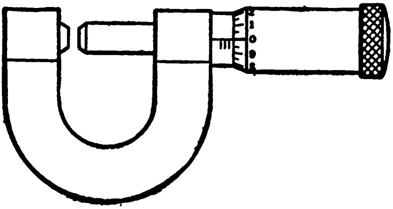

FIG. 38.—Micrometer caliper.

117. Elasticity is that property of a body by which it resists change of shape or volume, and returns to its original shape or volume when the distorting force is withdrawn.

All kinds of matter, whether solid, liquid, or gaseous, when compressed, will tend, to some extent, to regain their original bulk, or, in other words, possess elasticity.

Elasticity developed in a body by compression is, therefore, a general property of matter.

There are two general varieties of elasticity; viz., *elasticity of form or shape*, and *elasticity of volume or bulk*. The former is possessed by solids only; the latter is possessed both by solids and fluids.

Solids are the only form of matter which can be stretched, bent, or twisted. Elasticity resists any of these changes.

Elasticity of stretching, bending, or twisting is, therefore, a property peculiar to the solid condition of matter.

Elasticity of form, resisting stretching or tension, is seen in the return to its former length of a piece of caoutchouc, or india-rubber, or, in a lesser degree, in a wire after it has been stretched by a weight. Elasticity resisting bending or flexure is seen in the recoil of a bow which has been bent and then released. Elasticity resisting twisting or torsion is seen in the untwisting of a string or wire which has been twisted.

118. The Measure of Elasticity.—The degree of elasticity of a body is measured by the force with which it tends to regain its original shape or volume when that shape or volume has been changed by compression, stretching, bending, or twisting. Liquids and gases, when compressed, resume their original volume on the removal of the pressure, and, therefore, possess perfect elasticity of volume. Within certain limits of compression nearly every solid body will resume its original shape when relieved from compression, bending, stretching, or twisting, and is, therefore, elastic; but with many solids the *limits of elasticity*, or the limit beyond which any further compression, bending, stretching, or twisting would produce a permanent change of form, are small.

119. Crystalline Form.—We recognize an animal or plant by a certain form peculiar to it. In the same way many lifeless substances occur in forms, called *crystals*, peculiar to them. Although in most solids these crystals are too small to be seen, yet they nearly always exist. For example, snow is composed of crystals of beautiful shapes.

Crystals are more or less regular in shape, and although of many different forms, are all modifications of a few simple forms.

Experiment 31.—Place a quarter of a pound of common alum in as much hot water as will completely dissolve it. Strain the solution through a piece of muslin, and pour the clear liquid into a cup or bowl, in which has been placed a piece of rough stone wrapped with colored yarn. Set the liquid aside in a quiet place over night, and in the morning shining crystals will be found covering the stone. By slipping a thin knife under the stone, it may be readily separated from the bottom of the cup or bowl.

PROBLEMS

1. Assuming that the breaking strength of iron is 56,900 lbs. per square inch of cross-section, what force, in lbs. weight, will just break an iron wire one-tenth of an inch in diameter?

2. A filament of spun glass has a diameter of 0.01 millimetre. What would be the tenacity of such a filament, taking 6.48 kilos per square millimetre as the tenacity of glass?

3. What cross-section of oaken beam having a breaking strength of 14,600 lbs. per sq. inch will give the same tenacity as a circular rod of wrought iron one inch in diameter, with a breaking strength of 56,900 lbs. per sq. inch.

4. Which possesses the greater breaking strength, an oaken beam ten square inches in area of cross-section, having a tenacity per square inch of 14,600 lbs., or an ash beam nine square inches in area of cross-section, having a tenacity per square inch of 16,670 lbs.? How much greater?

CHAPTER VII

WORK, ENERGY, AND POWER

120. Work.—When force is exerted through a distance, *work* is done.

A car will not move of itself over a level road, but requires either to be drawn by a horse, steam engine, or electric motor, or to be pushed by a man. In other words, it requires force to act on it through a distance. When it is drawn or pushed over a track by any force, the amount of work done is measured by the force acting, multiplied by the distance through which it acts.

Work is never done by a force unless the force produces a motion of the body on which it is acting. A weight resting on a table exerts a pressure on the table, but does no work until the force of gravity, which causes the pressure of the weight, is permitted to produce a motion of the weight; *i. e.*, to cause it to move or to fall.

A coiled spring, as in the works of a watch or clock, exerts a pressure in attempting to uncoil itself, but it does no work until the force of elasticity is permitted to produce a motion.

When a body is moved by any force, it is said to have *work done on it.* The moving body causing the motion is said *to do work on the body* it moves. Thus, when a man moves a weight he is said to do work on the weight; when a falling weight moves the body which it strikes, the weight is said to do work on that body.

121. Elements of Work.—The elements of work are:

1. Force.
2. Distance.

Work is measured by the force which is acting, multiplied by the distance through which it acts. If a certain effort is required to lift a weight through a distance of one foot, it will require twice the amount of work to be done to lift this weight through two feet, or through twice the distance.

The equation for work is:

$$W = F S. \quad (16)$$

That is, the number of units of work done is equal to the product of the units of force exerted by the units of distance through which the resistance is overcome.

122. Energy.—The ability to do work is called *energy*. Whenever any work is done, energy is expended. As soon as a body expends its store or amount of energy, its ability to do work ceases.

All natural phenomena are caused by energy acting on matter. Physics is, therefore, sometimes defined as that branch of natural science which treats of matter and energy.

123. Transfer and Transformation of Energy.—Whenever energy is expended to produce a phenomenon, such energy must be drawn or transferred from some stock or store of existing energy. For example, when the spring of a clock is run down, and has thus expended the energy it possessed, it requires a new store or stock of energy to be again imparted to it; as by the muscular force of the hand that winds it up. When the raised weight has expended its energy by falling from the table to the ground, it requires that energy be again imparted to it, in order to raise it from the ground to the table.

Doing work or expending energy may also consist in a transformation of energy from one form to another; thus the man who wound the clock drew his store of energy from his food, which, after its assimilation by his body, had its chemical energy changed or transformed into muscular energy. The food, in its turn, received its energy by various transformations from the sun. The light emitted by an electric lamp is obtained by means of a transformation or change from the energy of the electric current that passes through it.

The energy required to drive a steam engine is derived from the steam. The steam drew this store of energy from the coal burned under the boilers. The coal received its energy from the sun during the growth of the vegetable matter from which the coal was formed. To produce any natural phenomenon an expenditure of energy is required. During this expenditure, certain transformations of energy take place, energy disappearing in one form and reappearing in another form, but in no case is any energy lost or annihilated, there being the same total amount of energy in the universe after the phenomenon has occurred as before.

124. The Unit of Work.—There are three units of work in common use. The unit of work used in scientific measurements is the *erg*. The work done when a force of one dyne is exerted through a distance of one centimetre is called an erg. As this is a very small unit, the *megerg*, one million ergs, is used for large quantities. The unit used when the force is expressed in kilograms and the distance in metres is called the ***kilogrammetre***.

The unit most frequently used in engineering in this country is the *foot-pound*. One foot-pound of work is done when a force of one pound weight is exerted through a distance of one foot.

The same amount of work is done when ten pounds are raised vertically through one foot as when one pound is raised vertically through ten feet, or five pounds through two feet, or two pounds through five feet; viz., ten foot-pounds.

When the work done is different from the raising of a weight, such as sawing a log of wood or crushing a lot of ore, it is convenient to express the amount of work done in foot pounds, as in raising a weight. This may always be done, since all work requires force to act through distance.

125. Power, Activity, or Rate-of-doing-Work.—By *power* or *activity* is meant the *rate-of-doing-work*.

A careful distinction must be drawn between the total expenditure of energy or the work done, and the rate at which this energy is expended, or the power.

Apart from the resistance of the air, the same amount of work is done in raising 100 pounds through one foot; viz., 100 foot-pounds, whether it be done in one second, in one minute, or in one hour. The rate at which the work is done, or the rate at which energy is expended in doing the work, is, however, quite different, being sixty times greater if done in one second than if done in one minute.

A unit of power is the foot-pound-per-second, or an expenditure of energy at the rate of one foot-pound per second. Another unit of power is the *erg-per-second.*

126. Horse Power.—Another practical unit or rate of doing work, employed in America and England, is the *horse-power*, a rate of doing work equal to 550 foot-pounds-per-second, or 33,000 foot-pounds-per-minute.

127. Systems of Units.—Units of measurement based on the English system, in which the foot, pound, and second are used, are called foot-pound-second or F. P. S. units. Those based on the French system, in which the centimetre, gram, and second are used, are called centimetre-gram-second or C. G. S. units.

1 metric horse-power = 75 kilogram-metres per-second.
1 English horse-power = 1.01385 metric horse-power.

One foot-pound equals 13,560,000 ergs, approximately. As the erg is so inconveniently small a number, ten million ergs, are taken as the *practical unit of work* in the C. G. S. system. This unit is called the *joule.*

1 foot-pound = 1.356 joules.
1 joule = 0.7373 foot-pounds.

The *C. G. S. unit of activity* is the *erg-per-second.* The practical unit of activity is the *watt*, or the *joule-per-second*, or a rate of expending energy equal to one joule-per-second. The watt is equal to 0.7373 foot-pounds-per-second.

128. Potential and Kinetic Energy.—A pound weight attached to a cord passing over a pulley requires ten foot-pounds of work to be done on it to raise it through a vertical distance of ten feet. If the raised weight be secured in position by fastening the end of the cord, the ten foot-pounds of energy are stored in the weight, and the energy so stored is called *potential* energy.

When the cord is cut, the weight falls, and when it reaches the ground, it has acquired a velocity such as will enable it to do an amount of work exactly equal to that expended on it in raising the weight to that distance of ten feet. This energy of motion is called *kinetic* energy.

129. Convertibility of Energy.—When a ball is thrown vertically upward all the energy it possesses at the moment it leaves the hand is kinetic; as the ball rises its energy gradually becomes potential, and when it reaches the highest point of its ascent, all its energy is potential. As it falls, its potential energy gradually becomes kinetic. At any point, either of its ascent or descent, the sum of its kinetic and potential energies is a constant quantity.

This alternate change of energy from kinetic to potential, or from potential to kinetic, naturally follows from the indestructibility of energy.

The pendulum affords an excellent illustration of the transformations of energy. When moved from its vertical position B, it is raised so as to be farther from the centre of the earth, as at A, and, therefore, contains potential energy. When released and allowed to swing, as it descends the arc it gains kinetic and loses potential energy. At the lowest point of the arc, B, while moving with the highest velocity, it has lost all potential energy and acquired the largest amount of kinetic energy. As it rises through the second quarter of its complete swing it loses kinetic and gains potential energy. At the highest point C, where its motion is reversed, it has lost all its kinetic energy and acquired the same potential energy as at first, except for that

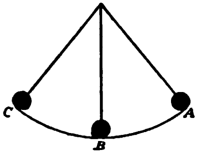

FIG. 39.

which has been used to overcome air resistance and friction. The total amount of energy remains the same, except for the gradual loss, as just noted, but the transformation from one kind to the other is continual.

130. Relation of Energy to Velocity.—The energy possessed by a body moving with a certain velocity may be estimated by determining the vertical height to which such velocity would raise it against the force of gravity. We can thus express the energy the body possesses in any of the units of work.

The power of a moving body to do work is increased by an increase of its velocity.

The amount of kinetic energy possessed by a moving body may always be determined by multiplying half its mass by the square of its velocity. The equations for energy are:

$$P.\,E. = Mgh. \quad (17)$$

Potential energy equals mass, multiplied by the weight of unit mass, multiplied by the height.

$$K.\,E. = \frac{MV^2}{2}. \quad (18)$$

Kinetic energy varies directly with the mass and the square of the velocity. This result will be in absolute units. If gravity units are desired, we use

$$K.\,E. = \frac{WV^2}{2g}. \quad (19)$$

where g equals the weight of unit mass or the acceleration given by the earth to a freely falling body (Par. 85).

For derivation of this formula, see Appendix.

131. Machines.—A machine is any arrangement of parts, by means of which force is so transmitted from one point to another that either its intensity or its direction, or both, are modified. The applied force which moves or drives a machine is called the *moving* or *driving force.* The force exerted by the machine is called the *weight, load,* or *resistance.*

Disregarding friction, in all machines the work done upon the machine is always equal to the work done by the machine.

A pair of scissors, Fig. 40, affords a good example of a simple machine. Here the driving force, which is the muscular force of the fingers, is applied at the handles, in a direction which causes the handles to come together. The work done by the scissors is the cutting of some material placed between the two blades.

FIG. 40.

The lever, or inflexible rod, $A\,B$, shown in Fig. 41, is another example of a simple machine. If the lever supported on the point F, nearer A than B, be moved until it assumes the position $A'\,B'$ then the distance $B\,B'$, through which the end B moves, will be greater than the distance $A\,A'$, through which the end A moves, in proportion as the distance $F\,B$ is greater than the distance $F\,A$.

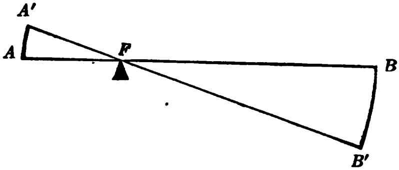

FIG. 41.

If the distance $F\,B$ is $2\frac{1}{2}$ times as great as $F\,A$, then a force of one pound weight applied at B will balance $2\frac{1}{2}$ pounds at A, or conversely, a force of $2\frac{1}{2}$ pounds weight at A will balance one pound at B.

These two forces balance each other because the work done at one end of the lever equals the work done on the other end. When, for example, a force at B balances a force at A, the work done by B exactly equals that done by A. Suppose, for example, the lever be used to raise a stone through the distance $A\,A'$, equal to one vertical foot. Then a force of 100 pounds weight applied at B will raise a weight of 250 pounds at A. To do this, the end B moves through the distance $B\,B'$, of $2\frac{1}{2}$ feet. But a force of 100 pounds weight exerted through a space of $2\frac{1}{2}$ feet equals 250 foot-pounds of work, and this is exactly equal to the work done on A; viz., 250 lbs. raised through the space of one foot, or 250 foot-pounds.

In general, equilibrium will result in any machine when the applied force, multiplied by the distance through which it acts, is equal to the force exerted by the machine, multiplied by the distance through which it acts.

Let F equal the applied force and d the distance through which it acts, and let R equal the resistance overcome and D the distance through which it is overcome; then

$$Fd = RD. \quad (20)$$

This, of course, is merely a special form of the equation for work, and means that the work put into the machine is equal to the work done by the machine.

This principle will enable us to determine the relation existing between the work expended in driving any machine and the work done by the machine; for, disregarding friction, we have only to notice that the work done by the driving force must equal the work done against the load. Suppose, for example, in any machine, that work is being done on it at the rate of 10 foot-pounds per second, and that the load is one pound weight, then if no work is expended within the machine, the output must be 10 foot-pounds per second, and the weight, if lifted vertically, will be raised 10 feet per second.

132. No Machine Creates Energy.—Since in every machine the work done by the driving force is always equal to the work done on the resistance, it is clear that no machine creates energy. A machine may increase the intensity of the working force, but can never increase the amount of energy.

In the preceding example, Fig. 41, a force of 100 pounds weight applied at B overcame a resistance of 250 pounds weight at A. This gain, however, was at the expense of the distance through which it moved; for the weight at A moved $2\frac{1}{2}$ times more slowly than the force at B. *Therefore, what a force gains in intensity it loses in the distance through which it moves.*

If a weight of 250 pounds be applied at the end A, it will raise a weight of 100 pounds at B, but it will raise it $2\frac{1}{2}$ times more rapidly. *Therefore, what a force loses in intensity it gains in the distance through which it moves.*

Although a machine gains nothing in energy, it may gain considerably in convenience. To make this clear, suppose that, by exerting his entire strength, a man could lift just 300 pounds. Then, by the use of a machine, such as a lever, he could raise say 300 × 10 = 3000 lbs.; but to raise these three thousand pounds through one foot, he would be required to exert a force of three hundred pounds weight through ten feet; and this would clearly be the same as if he divided the three thousand pounds into ten separate parcels of three hundred pounds each, and, for ten successive times, exerted his strength of three hundred pounds weight through a single foot.

In general, whatever be the nature of the work for which the machine is designed, its perfection depends on the convenience it secures in the performance of that work.

133. Advantages Gained by Machines.

1. Machines may enable us to increase the effective intensity of a force by causing it to act through a smaller distance; or, they may enable us to permit the force to act through a greater distance at a corresponding expense of intensity.

2. Machines may enable us to change the direction in which the force is applied, thus affording a great convenience. For example, a cord passed over a pulley may be applied more advantageously for the raising of a weight than by raising the weight directly.

3. Machines may enable us to apply other forces than our muscular force, such as the force of the wind, of running water, or of steam.

134. Laws of Machines.—The work done by any machine consists of two distinct parts:

1. The useful work or the *output; i. e.*, that done by the machine in performing the work for which it was designed.

2. The useless or wasted work, or that done by the machine against the friction of the moving parts or the resistance of the air.

The sum of the useful and wasted work must be equal to the work expended in driving the machine, or the *intake.*

The *efficiency* of a machine is the quotient obtained by dividing the output by the intake. An efficiency of 0.95, or 95 per cent. indicates, that 5 per cent. of the energy is wasted in internal work. Therefore, the smaller the waste, the greater the efficiency of the machine. The efficiency can, of course, never exceed 100 per cent.

135. The Mechanical Powers are the *lever*, the *wheel and axle*, the *pulley*, the *inclined plane*, the *wedge*, and the *screw*.

These six mechanical powers are, in reality, modifications of the lever and the inclined plane.

In the following statements relative to simple machines, it is, for convenience, assumed that no energy is wasted during its transmission from one part of the machine to another.

136. The Lever.—A lever consists of an inflexible rod or bar moving about a fixed point, called the *fulcrum*.

A force applied at one end of the lever overcomes a resistance, or lifts a weight, at another part.

The different forms of levers may be arranged in three classes, according to the relative positions of the fulcrum, and the points of application of the force and of the weight.

In levers of the first class, Fig. 42, the fulcrum is between the force and the weight; in levers of the second class, Fig. 43, the weight is between the fulcrum and the force; and in levers of the third class, Fig. 44, the force is applied between the fulcrum and the weight.

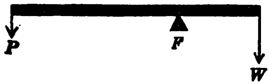

FIG. 42.—Lever of first class.

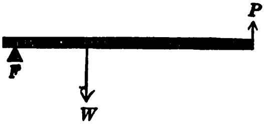

FIG. 43.—Lever of second class.

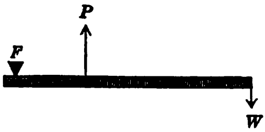

FIG. 44.—Lever of third class.

Examples of levers of the first class are found in a pair of scissors; in a crowbar, when used to raise blocks of stone; in the common balance for weighing, and in a pair of pincers.

Examples of levers of the second class are found in nut-crackers, Fig. 45, where *W*, the nut to be cracked, is placed between the fulcrum *F*, and the part *P*, where the force is applied. A wheelbarrow is another example in which the fulcrum is at the wheel; the force is applied at the handles, while the weight is between the two.

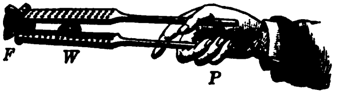

FIG. 45.

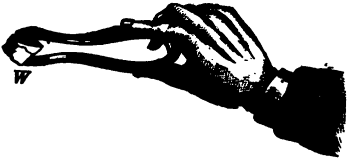

FIG. 46.

Examples of levers of the third class are found in the sugar-tongs, Fig. 46, in the fire-tongs, and in the common foot-treadle.

137. Advantage of a Lever.—In order to calculate the effects produced by any lever we must know:

1. The points of application of the force and of the resistance or weight.

2. The position of the fulcrum; or, in other words, the relations existing between the arm of the force and the arm of the weight.

The *arm of the force* is the perpendicular distance from the fulcrum to the direction in which the force acts. The *arm of the weight* is the perpendicular distance from the fulcrum to the direction in which the weight acts.

The product of the force and the arm of the force is called the *moment* of the force. The condition of equilibrium for any lever is reached when the moment of the force is equal to the moment of the resistance.

When the force acts, as in Fig. 47, in a direction, $B\ P$, at right angles to the length of the lever, then $F\ B$ is the arm of the force; but if it acts in any oblique direction, as $B\ P'$, then FB', the perpendicular distance from the fulcrum to the direction $B' P'$, of the force, is the arm of the force. The moment of the force P is $P \times FB$. The moment of the weight

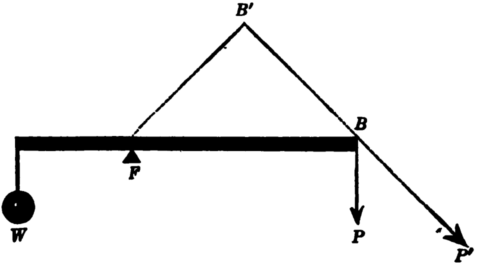

FIG. 47.

W is $W \times FA$. If motion does not take place around the fulcrum F as a center, the lever is in a state of equilibrium, and $P \times FB = W \times FA$. Therefore,

$$W = P \times \frac{FB}{FA}.$$

The mechanical advantage of a lever is, therefore, equal to the inverse ratio of the lengths of its arms.

Writing this equation as a proportion, and using general terms, we have:

Power : Resistance :: Resistance arm : Power arm. (21)

138. Compound Levers.—Where it is desired to obtain a very great difference between the length of the arm of the force and the arm of the weight, in order to avoid inconvenience, a number of levers are employed, in which the arm of the resistance in the first lever acts directly against the arm of the force on the second; and the arm of resistance of the second, against the arm of the force of the third, and so on throughout all the levers. Hay scales usually employ compound levers.

139. The Wheel and Axle.—In the wheel and axle force applied at the circumference of a wheel is employed to raise a weight attached to a rope wound around the axle. Fig. 48 shows a form of wheel and axle called the *windlass*. The force, applied either to a wheel or winch at *W*, raises a weight *B*, attached by a rope to the axle *A*. The wheel and axle is a modification of the lever; the fulcrum is at the axis, the arm of the force is the radius of the wheel, and the arm of the weight is the radius of the axle.

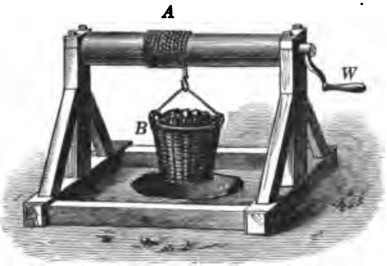

FIG. 48.—The windlass.

Since, by one complete turn of the wheel, the weight is raised only the length of the rope wound once around the axle, a force of a pound weight applied at the wheel will raise a weight of as many pounds, hung to the axle, as the circumference of the wheel is times the circumference of the axle.

Thus, if the handle *W* of the windlass shown in Fig. 48 be at a distance of two feet from the axis, and if the radius of the barrel, on which the rope is wound, be three inches, then the leverage of the windlass will be $\frac{24}{3}$ or 8 to 1, and the hand must move through eight times the distance through which the bucket moves. If the bucket weighs 100 lbs. and be lifted through a total distance of 100 feet, the work done will be 10,000 foot-pounds, and the hand will be moved through 800 feet with a force of 12.5 lbs. weight, making the work done by the hand, disregarding friction, 10,000 foot-pounds.

Water wheels and steering gear for vessels employ the principle of the wheel and axle.

140. Trains of Wheel-work.—Where it is desired to obtain a considerable difference between the diameter of the wheel and the diameter of the axle, a number of smaller wheels and axles are combined into what is called a *train of wheel-work*.

The force applied to the first wheel transmits its effects to its axle, which acts on the second wheel, and the axle of the second wheel transmits its effects to the next wheel, and so on, throughout the entire train.

Equilibrium results when the force, multiplied by the continued product of the radii of all the wheels, equals the weight, multiplied by the continued product of the radii of all the axles.

A train of wheels is shown in Fig. 49. The wheel on which the driving force is applied is called the *driver*. The wheel which exerts the force is called the *driven wheel*, or the *follower*.

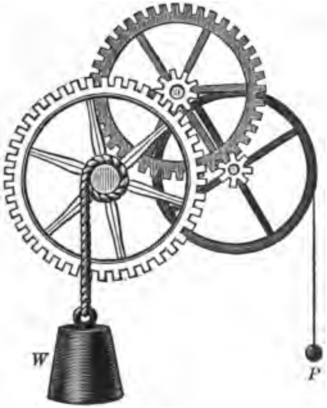

FIG. 49.—Train of wheels.

If, as in the figure, the radius of each wheel is six and its axle one, then, disregarding friction, one pound at P will balance 216 pounds at W.

Trains of wheel-work are used either where great weights are to be lifted by a small power, as by cranes, or, for the purpose of obtaining differences in the velocity, as in clock-work.

141. The Pulley consists of a wheel turning on its axis, and having an edge over which a flexible band or rope passes. Pulleys may be *fixed* or *movable*. The fixed pulley is shown in Fig. 50.

The pulley, like the wheel and axle, may be considered as a continuous lever, the fulcrum of which is at F.

The arms of the weight and force *F w* and *F f* are equal to each other, so that no advantage is gained except as to the direction of the motion, since, if the rope is pulled down one foot by the force, it will raise the weight through an equal distance. In practice, owing to the existence of friction, the force applied by the hand must be greater than the force exerted by the weight. The fixed pulley is a lever of the first class with equal arms.

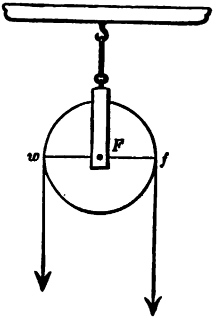

FIG. 50.—Fixed pulley.

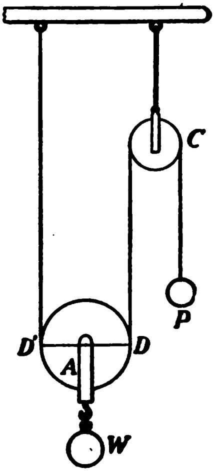

FIG. 51.—Movable pulley.

In the *movable pulley*, Fig. 51, the block or frame *A*, to which the weight is attached, is movable. It may be considered as a lever of the second class with unequal arms. The force is applied at *D*, the weight at *A*, and the fulcrum is at *D'*. The force arm, *D D'*, is, therefore, the diameter and the weight arm *A D'* is the radius of the wheel. The mechanical advantage is, therefore, *two*.

According to the law of machines $Fd = RD$. Here $F = P$, $d = DD'$, $R = W$, and $D = AD'$. Therefore, $P \times 2r = W \times r$ or $P = \frac{W}{2}$ or

$$W = 2P. \quad (22)$$

Like the wheel and axle or the lever, pulleys are sometimes compounded. In the compound pulley, shown in Fig. 52, which contains three movable and three fixed pulleys, in order to raise the weight one foot the force must move through twice as many feet as there are movable pulleys, or through six feet, and one pound at *P*, will, therefore, balance (neglecting friction) 6 lbs. at *W*.

142. The Inclined Plane.—Instead of raising a weight directly through a given height, it may be raised gradually through the same height, by moving it up an inclined plane. In this way heavy casks or barrels are moved out of deep cellars.

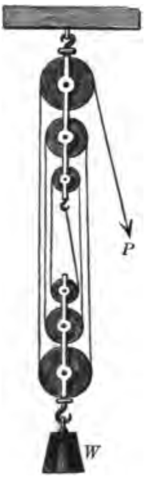

FIG. 52.—Compound pulley.

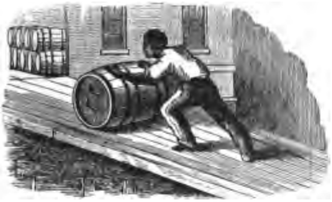

FIG. 53.—Inclined plane.

An example of the inclined plane is seen in Fig. 53, where, to raise the barrel through a height equal to the height of the plane we must roll the barrel over the whole length of the plane. Or, the force to be applied to raise the barrel must be equal to the weight multiplied by the height of the plane, divided by its length.

If the length of an inclined plane be four times as great as its height, a force of one pound weight will be able to move a weight of four pounds up the plane.

From the equation $W = FS$, we see that by increasing one of the factors we may decrease the other. In the inclined plane S is made larger in order that F may be smaller. So that if the weight to be lifted is large, by exerting a smaller force through a greater distance the same result may be accomplished. The amount of work done is no less, but a smaller force is applied and exerted through a greater distance.

The usual method of using an inclined plane is to apply the power parallel to the length of the plane. We may find the mechanical advantage under these circumstances by applying the equation for work. If the body is moved from C to A up the plane by the force F, the work done equals $F \times AC$. But during this movement the work done on the body is $W \times AB$, since the weight is lifted through the vertical height AB; therefore, $F \times AC = W \times AB$.

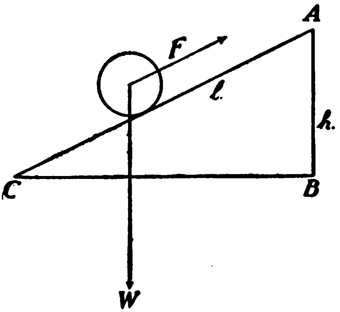

FIG. 54.

Since AC = the length = l,
And AB = height = h, we have

$$F \times l = W \times h \text{ or } W = F \times \frac{l}{h}. \quad (23)$$

In this case the mechanical advantage is equal to the ratio of the length of the plane to its height.

143. The Wedge.—The wedge is a modified form of inclined plane, in which, instead of moving the weight up, the plane is moved under the weight. The wedge is used when great force is to be exerted in a small space, as in splitting wood or stone, Fig. 55, or in pressing oils or juices from seeds. The edge of such cutting tools as scissors, knives, chisels, hatchets, and razors are forms of wedges.

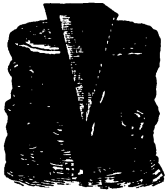

FIG. 55.—The wedge.

144. The Screw is another modification of the inclined plane, and bears the same relation to a simple plane that a spiral staircase does to a straight staircase. If a piece of paper be cut in the form of a right-angled triangle and wrapped around a cylinder, as shown in Fig. 56, the edge of the paper, which corresponds to the length of the plane, will form a spiral line around the cylinder, in a direction which will be the same as that of the thread of a screw. As the force which turns the screw moves it through one complete turn, the screw, and anything

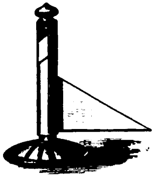

FIG. 56.—The screw.

against which it is pushing, as, for example, the movable plate of a copying press, Fig. 57, advances through the distance between two consecutive threads. If the power acting on a screw moves through a circumference of 24 inches, and the distance between any two consecutive threads be $\frac{1}{10}$ of an inch, a force of one pound applied at the head of the screw would move a weight of 240 pounds at the other end, since the power would move through a distance 240 times as great as that through which the weight moves.

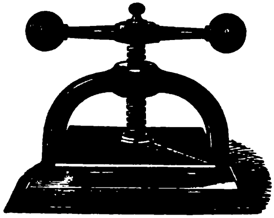
FIG. 57.

In the case of the screw, equilibrium results when the circumference at which the force is applied bears the same proportion to the pitch of the screw as the resistance bears to the applied force.

Thus, if a copying-press has a screw of four threads to the inch, and the circumference at which the force is applied by the hands is thirty inches, then, disregarding the friction of the screw, a force of thirty pounds weight applied at the handle will produce a pressure on the copying-book of 30 × 120 = 3600 lbs. weight.

From the general equation for machines $Fd = RD$ we derive the formula for the screw as follows: P = force, d = distance through which it moves = circumference of the circle = $2\pi r$. R = weight raised or pressure produced. D = distance screw advances during one turn = pitch = p. Therefore,

$$P \times 2\pi r = W \times p \qquad W = P\frac{2\pi r}{p}. \quad (24)$$

145. Compound Machines.—No matter how great the complexity of a machine, it consists of various combinations of some or all of the simple machines, or mechanical powers, just described; viz., of the lever, the pulley, the inclined plane, the wedge, and the screw. In all cases the advantage of the machine may be determined by calculating the effect of each simple machine separately and then combining the results.

If, in any case, the distance through which the force and the weight move can be directly measured, then, disregarding friction, the force multiplied by the distance through which it moves will be equal to the weight multiplied by the distance through which it moves.

146. Perpetual Motion.—Many persons, ignorant of the fact that machines do not create energy, but only transmit the energy imparted to them, have vainly endeavored to design a machine that, once set in motion, should not only continue to move forever afterward, but should even give energy to other bodies, without losing any of its own energy.

If a body could be set in motion in a place where it would be exposed to no friction nor fluid resistance, it would continue to move forever. Such conditions, however, are impossible, and even if they did exist, such a machine would be useless, since it would possess only a certain quantity of energy; namely, the energy applied to start it; and if employed to impart motion to other machines or to do any work, it would cease moving as soon as it had expended an amount of energy equal to that originally imparted to it.

PROBLEMS

1. A man lifts a hod of bricks weighing 50 lbs. through a vertical distance of 50 feet. What amount of work will he necessarily perform in the process expressed in foot-pounds?

2. A boy weighing 80 lbs. runs up a flight of stairs having a total difference of elevation of 100 feet. How much work does he expend in lifting his weight against gravitational force? Express result in foot-pounds.

3. If, in the last case considered, he ran up the stairs in thirty seconds, what would be his average activity in foot-pounds per second?

4. A racing row-boat is propelled by eight oarsmen at a speed of 1000 feet per minute, and with an average force equal to 80 lbs. weight applied horizontally at the bow of the boat. What is the average activity of each oarsman in foot-pounds per minute?

5. The Atlantic liner "Paris" is stated to indicate 20,000 horse-power. Assuming that she steams across the Atlantic in six days, what total amount of work does she perform on the journey, in foot-pounds?

6. In a windlass, such as shown in Fig. 48, page 92, the circumference described by the handle *W* is six feet. The circumference of the axle on which the rope is wound is one foot. Then, disregarding the weight and thickness of the rope, what weight can be raised by a force of thirty pounds' weight applied at *W?*

7. In a movable pulley, such as shown in Fig. 51, page 94, what force, at *P* disregarding friction, will be required to raise 2240 lbs. at *W?*

8. What force would be required in the case of the compound pulley shown in Fig. 52, page 95, to be applied at *P*, to raise the same weight when hung at *W?*

9. The screw of a copying press has five threads to the inch. If the handle at which the power is applied moves through a circumference of four feet, then, disregarding friction, what pressure will be exerted on the copying book by a force of 50 lbs. weight applied at the circumference?

10. A barrel of sugar weighing 300 lbs. is to be rolled into a wagon 4 ft. above the ground by means of an inclined plane. If the plank is 12 ft. long, what force must a man exert?

11. What length must be given to a plane in order that a force of 20 kg. can support a weight of 400 kg., the height of the plane being 4 m.?

12. With a lever of the first class 12 ft. long, the fulcrum being 3 ft. from the end, how much can a man lift who exerts a force of 150 lbs. weight?

13. With which class of lever can a force of 50 lbs. weight

raise the greatest weight, if the lever is 10 ft. long and the weight arm is 2 ft. long? Prove the answer by a figure for each case.

14. In a lever of the third class 15 ft. long, the power moves 10 in., the power arm being 3 ft. long. How far does the weight move?

15. If the wheel of a bicycle is 28 in. in diameter, the small sprocket 3 in., and the large sprocket 9 in., how many times will a man need to move his right foot up and down in going a half mile?

16. Twelve jackscrews each of which has a pitch of $\frac{1}{5}$ in. and a lever arm of 20 in. are being worked together to raise a building weighing 150,000 lbs. Neglecting friction, what force would have to be exerted at the end of each lever?

17. 700,000 tons of water fall every minute at Niagara over a height of about 160 ft. What horse-power would this give if all the energy could be utilized?

PART II

FLUIDS

CHAPTER VIII

HYDROSTATICS

147. Fluids, or bodies that flow, are either liquids or gases.

The phenomena of the rest and motion of fluids may be studied under the heads of—

(1) *Hydrostatics*, which treats of liquids at rest.

(2) *Hydraulics*, which treats of liquids in motion.

(3) *Pneumatics*, which treats of gases either at rest or in motion.

148. Compressibility of Liquids.—Liquids are but slightly compressible. Water, when subjected to a pressure of fifteen pounds to the square inch, is compressed only the $\frac{1}{20000}$ of its volume. Many other liquids are even less compressible.

Liquids, as a rule, however, are more compressible than solids. Usually when solids are compressed, they are not confined at the sides. The particles, therefore, spread. Solids, therefore, appear to be more compressible than liquids. If, to prevent solids from spreading laterally, we should confine them in strong vessels, as we must do with liquids, we should find solids to be less compressible than liquids.

The molecules of liquids possess great freedom of motion; they slip, slide, or move over one another with practically no resistance.

149. Pascal's Law of Transmission of Pressure.—*Liquids transmit the pressure exerted on any part of their mass in all directions and without loss of intensity: this pressure acts with equal force upon equal areas and at right angles to them.*

Liquids transmit pressure equally well in all directions because of the great freedom with which their molecules move in any direction over one another; moreover, liquids experience no loss in transmitting pressure from any part of their mass to any other part.

150. Liquid Pressure as a Mechanical Power.—Since pressure is transmitted through liquids as well in one direction as in another, and without any loss of intensity during the transmission, the total pressure sustained by any surface is proportional to its area. Liquid pressure, therefore, furnishes us with an additional mechanical power.

If, for example, two vessels, *A* and *B*, Fig. 58, filled with water, be furnished with pistons, *C* and *D;* that is, with parts arranged so as to move freely up and down the vessels, without allowing the water to pass them, and these vessels be connected by a tube *T*, we have a simple machine, or practically, a mechanical power, by which we can modify the effect of a force to any desired extent. Suppose the areas of the two pistons *C* and *D* be respectively 1 and 100 square inches. If the piston *C* be pushed down with a force of 1 lb. weight, the piston *D* will be raised with a force of 100 lbs. weight; for, since a pressure of 1 lb. weight at *C* is exerted on the area of one square inch, it exerts a pressure of 1 lb. weight on every square inch of surface in the two vessels. But the piston *D* is the only other part of the vessel that can move, and, as it contains 100 square inches, it must be pushed upward with a force of 100 lbs. weight.

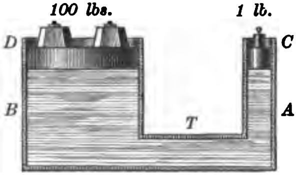

FIG. 58.

As in any other machine, the work expended at the end where the force is applied is equal to the work done at the end where the resistance is overcome. In the above case, if the piston *C* be moved through 1 ft, *D* would be raised through the $\frac{1}{100}$ ft. But 1 lb. weight × 1 ft. = 1 ft.-pound, and $\frac{1}{100}$ ft. × 100 lbs. weight = 1 ft.-pound.

151. The Hydrostatic Press.—The machine just described forms what is known as the hydrostatic press. A lever *P*, Fig. 59, is attached to the piston *A*, and by its movement oil or water is pumped into the larger vessel in which the piston *B* moves. The pressure thus exerted causes the piston *B* to rise. Substances to be compressed, such as hay or cotton, are placed between a platform *C*, attached to the piston *B*, and a strong frame *D*, attached to the press.

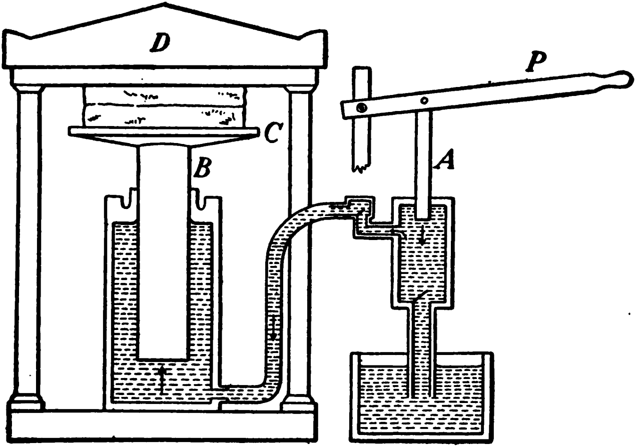

FIG. 59.

The hydrostatic press is employed in the arts for a variety of purposes where great pressure is required, such as raising heavy weights; extracting oil from seed; compressing hay or cotton; moulding plastic material, like clay, in the manufacture of bricks, terra-cotta, etc.

152. Pressure Caused by the Weight of a Liquid.—Every part of a liquid has to bear the weight of all the liquid directly above it. The greater the depth of the liquid, the greater will be the amount of liquid above this part; therefore, the pressure exerted by any liquid increases with the depth of the liquid. The pressure exerted by any liquid increases also with its density; for example, a vessel filled with mercury or with molasses will have a greater pressure on its sides and base than if it were filled with water, because mercury or molasses is denser than water.

As liquids exert pressure equally in all directions, the downward, upward, and lateral pressures at any point within the liquid must balance one another.

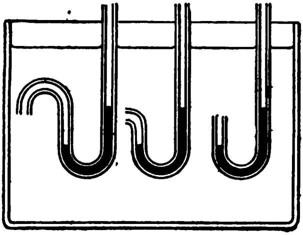

FIG. 60.—Pressure in a fluid.

Bend three glass tubes of the same diameter into the forms shown in Fig. 60, having the short arms so bent that they open in different directions—upward, downward, and sidewise. Put mercury in them until it stands at the same height in each. Now lower one of them slowly into a tall jar filled with water. As it descends, the mercury will rise. This shows that the pressure is proportional to the depth. Now put all three tubes into the water and adjust so that the openings are all on the same level. The mercury will be found to be at the same height in each. This shows that the pressure at a point in a liquid is the same in all directions.

153. The Downward Pressure or the Pressure on the Base.—The pressure on the horizontal base of a vessel filled with liquid depends only on the area of the base and the depth of the liquid. The amount of this pressure may be greater than, equal to, or less than, the weight of liquid in the vessel.

If the vessel has vertical walls as at A, Fig. 61, the pressure on its base will be exactly equal to the weight of the liquid in the vessel; if the walls are inclined as at B, the pressure on the base is the same as at *A*, and is greater than the weight of the contained liquid; if the walls are inclined as at C, the pressure on the base is the same as at *A*, and is less than the weight of the contained liquid.

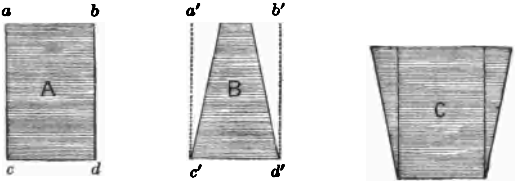

FIG. 61.—The pressure on the base.

It might be supposed that the total pressure on the base of any vessel would always equal the weight of the liquid in the vessel; but in the vessel B, the particles at the surface not only transmit their pressure to those parts of the base directly under them, but also to all parts of the base $c' d'$. The total pressure on the base, therefore, is the same as if there was the same depth of liquid over all parts of the base as there is over the middle parts; that is, the total pressure is equal to the height of the column of water, $a' b' c' d'$. In the vessel C only the particles of the liquid immediately above the base exert a pressure on the base; the inclined walls receive the pressure of the remaining particles.

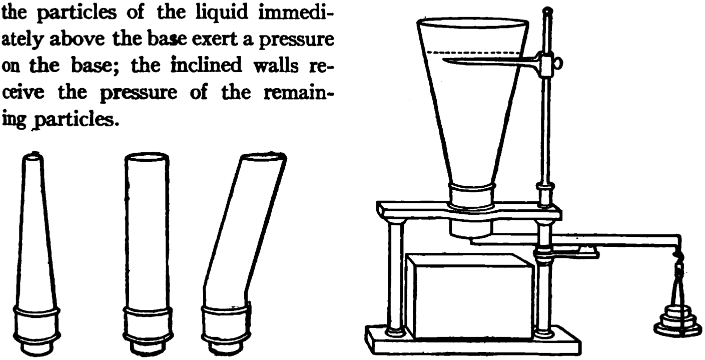

FIG. 62.—Pascal's vases.

If, therefore, different vessels having horizontal bases of the same area are filled to the same depth with water, the pressure on the base of each vessel will be the same, although the shape of the vessels and the quantity and weight of water in the vessels may differ. The principle that the pressure on the base of a vessel does not depend upon its shape and capacity is known as the *hydrostatic paradox.*

The so-called hydrostatic paradox may be clearly illustrated by the apparatus called Pascal's vases (Fig. 62). Vessels of various shapes and capacities, but fitting the same base, are filled with water to the same height, when it is found that the pressure exerted on the base is the same no matter what the volume of the water may be.

154. Total Pressure Expressed as Weight.—In calculating the pressure produced by the weight of any liquid in a containing vessel, it is convenient to express such pressure as equal to the weight of so many cubic inches or cubic centimetres of water.

The total pressure on the base of a vessel containing any liquid is equal to the weight of a column of liquid whose base is that of the vessel, and whose height is equal to the vertical distance from the middle of the base to the surface of the liquid.

Pressures are commonly expressed by the height of the liquid in the containing vessel above the point considered. Thus we frequently speak of a pressure of, say, 3 inches of water, meaning the total pressure of a column of water 3 inches high on an area of one square inch.

To calculate the total pressure in pounds weight on a horizontal base, multiply the area of the base in square inches by the depth of the water in inches, and the product by the weight of a cubic inch of water; *i. e.*, 0.03612 lb. weight. Thus a bucket with a base 50 sq. in. in area, filled with water to a depth of 10 inches, supports on its base a total pressure of $50 \times 10 \times 0.03612 = 18.06$ lbs. weight. The use of the metric system of weights and measures greatly simplifies such calculations, for the area of the base in sq. cms. multiplied by the depth in cms. gives at once the total pressure in grams weight, since 1 c.c. of water weighs one gram. Thus, in the preceding case, 50 sq. in. = 322.6 sq. cms. and 10 in. = 25.4 cms., so that the total pressure on the base of the bucket $= 322.6 \times 25.4 = 8192$ grams weight = 18.06 lbs. weight.

155. Pressure on the Sides of a Vessel.—The pressure on any vertical side of a vessel containing liquid is equal to the weight of a volume of the liquid, obtained by multiplying the area of that side by the vertical distance from the centre of gravity of the side to the surface of the liquid.

This may be expressed by the formula

$$P = H a w. \quad (25)$$

Where P = pressure, H = height of liquid above the centre of gravity of the surface, a = area of surface and w = weight of unit volume of the liquid.

In a rectangular vessel filled with water the centre of gravity of the side will be at its geometrical centre; *i. e.*, at the intersection of diagonals drawn from opposite corners, or half way up the side.

A rectangular vessel 3 feet long, 2 feet wide, and 1 foot deep, when filled with water, has exerted on each of its longer sides a total pressure equal to the weight of 3 feet of water; for the area of each of these sides is 3 × 2 = 6 sq. ft., which multiplied by half the height = 3 cubic feet. Since the weight of one cubic foot of water = 62.4 lbs., the total pressure is 62.4 × 3 = 187.2 lbs. weight.

156. Upward Pressure.—The upward pressure in pounds weight at any surface in water is equal to the downward pressure at that surface, and is, therefore, equal to the area of the surface, multiplied by its depth below the surface of the liquid, multiplied by the weight of one cubic inch of water. Or, expressed in grams weight, the pressure is equal to the area in sq. cms. multiplied by the depth in cms.

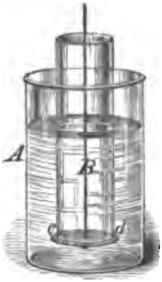

FIG. 63.

The area of the base *c d*, Fig. 63, is one square inch, and the water over it is 12 inches deep. Then the upward pressure is 1 × 12 × .036 = .432 lb. weight. The quantity .036 is the weight of a cubic inch of water. If the area of *c d* were 1 sq. cm. and the depth below the surface were 10 cm., then the upward pressure would be 1 sq. cm. × 10 cm. × 1 gram = 10 grams weight.

Experiment 32.—Procure a glass chimney, *B*, Fig. 63, with straight sides and smooth ends. Cut a disc, *c d*, of mica, such as is used for the doors of stoves, large enough to cover the base of the chimney. Attach a string to the middle of the disc. Now, placing the disc so as to cover one end of the chimney, and holding the disc against the end by the string, push the chimney vertically downward into a vessel *A*, filled with water. Observe that after some little depth has been reached, the string need no longer be held, as the total upward pressure, caused by the water in *A*, endeavoring to flow into *B*, will hold the disc in its place.

To find the amount of this total upward pressure, pour water into the chimney, or let the water gradually leak into the chimney at the base until the disc falls off, which will take place when the level of the water in the chimney is the same as on the outside. At this moment the total downward pressure, caused by the water in *B*, is equal to the total upward pressure caused by the water in *A*. Since the sides of the chimney are vertical, the total downward pressure is equal to the weight of the water in *B;* hence the total upward pressure on *c d* is equal to the weight of a column of water whose base is *c d*, and whose height is the depth of the liquid above *c d*. As the mica disc has some weight, which acts downward, the height of the water in *B* will not quite equal that of the outside level when the disc falls off.

157. Surface of Liquids at Rest.—When a liquid is at rest, its upper surface is level or horizontal; for, were it higher at one point than another, the greater pressure so produced would press it up at the lower points until the entire surface became level.

It is the surface of only a comparatively small extent of water that may be regarded as plane. Large water surfaces, like those of the ocean, are curved. For any mass of water to be in equilibrium, all parts of its free surface must be at right angles to the plumb line.

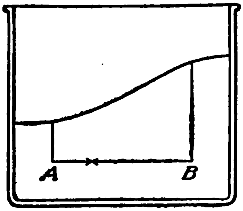

FIG. 64.

Suppose the surface of a liquid in a vessel has been forced to take the shape shown in the diagram, as by a sudden jar. Consider the two particles *A* and *B* in the same horizontal layer. The pressure upon each is proportional to the depth below the surface. Therefore, the downward pressure upon *B* is greater than that upon

A. As pressure in liquids is equal in all directions, the particle *B* is forced toward *A*, with a force greater than that with which *A* is forced toward *B*. The particle *B*, therefore, comes toward *A* and the surface above *B* falls, while that above *A* rises until the surface of the liquid becomes level.

158. Equilibrium of Liquids in Communicating Vessels.—A liquid placed in communicating vessels is in equilibrium when its level stands at the same height in all the vessels; for, were it higher in one vessel than in the others, the greater pressure so produced in the highest vessel would cause the liquid to mount in the other vessels until it stood at the same height in all. Water rises from the pipes in the streets of a city, and fills the pipes in the houses, because the level of water in the basin or reservoir in which it is stored is equal to or greater than the height of the houses.

As we have already seen, liquids in capillary tubes form an exception to this statement, the level being higher when the liquid wets the walls of the tubes, and lower when it does not wet them.

In artesian wells, water is forced up from great depths by the pressure of water contained between two curved impervious or water-tight strata. Fig. 65 shows a section of an artesian well. The liquid is forced up through the well, and caused to escape at the surface, by reason of the pressure of the

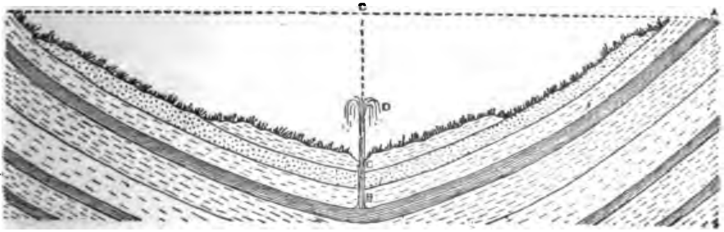

FIG. 65.—Artesian well.

liquid at a higher level, contained between the impervious strata.

Two liquids of different densities placed in communicating vessels will be in equilibrium when the level of the denser liquid is as much lower than the level of the lighter liquid as the density of the former is greater than the density of the latter. In other words, the heights of liquid columns of different densities in communicating vessels are inversely as the densities.

159. Archimedes' Principle.—Buoyancy.—Bodies immersed in a liquid apparently weigh less than in air, losing an amount of weight equal to the weight of the liquid they displace. This important principle was discovered by Archimedes.

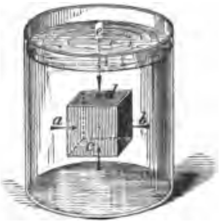

FIG. 66.

Suppose the cube *a b c d*, Fig. 66, be completely immersed in water. Consider the manner in which the pressures exerted on its surfaces by the liquid affect the weight of the cube. The pressures on the opposite vertical sides, being equal, will neutralize each other. The downward pressure on the top is equal to the weight of a column whose base is equal to the top of the cube, and whose height is the depth of the liquid *e d* at this surface; the upward pressure on the base is equal to the weight of a column of liquid whose base is equal to the bottom of the cube, and whose height is *e c*. The upward pressure, therefore, exceeds the downward pressure, by a weight of water equal to the weight of the volume of the cube.

This excess of upward pressure, being exerted in a direction opposite to that of the force of gravity, will cause the cube apparently to lose an amount of weight equal to the weight of the water it displaces; this apparent loss of weight is due to the excess of the upward pressure over the downward pressure and is called *buoyancy*.

Let a represent the side of the cube, and b the distance of the upper surface, below the surface of the water. Then the pressure on the upper surface, $Haw = a^2bw$. The pressure on the lower surface $= a^2w\ (a + b) = a^3w + a^2bw$. As these act in opposite directions, the effect produced is due to their difference, which is a^3w. But as a^3 is the volume of the cube, this shows that the apparent loss of weight is equal to the volume of water displaced.

160. Experimental Proof of the Principle of Archimedes.—The correctness of the principle of Archimedes may be demonstrated by means of the apparatus shown in Fig. 67. A closed cylinder *B*, of such a size as exactly to fill the hollow cylinder *A*, is suspended below it, the two attached to the pan of a balance, and counterpoised in air by weights at *C*. The cylinder *B* is then completely immersed in water, as shown in the figure. The buoyancy of the water on the cylinder *B* causes it apparently to lose weight, as is shown by the other pan of the balance falling. If, now, the cylinder *A* be exactly filled with water, equilibrium will be restored. The weight apparently lost by *B*, therefore, is equal to the weight of a volume of water which will just fill *A*; but this volume is the same as that displaced by *B*; therefore, the weight apparently lost by *B* is equal to the weight of the water it displaces.

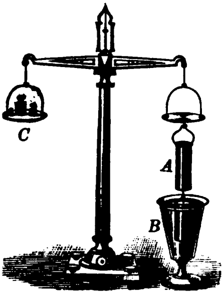

FIG. 67.

161. Floating Bodies.—A body placed in a liquid will float if it displaces a volume of liquid equal to its weight, because the buoyancy of the liquid, which holds the body up, is equal to the force of gravity, which pulls it down.

Buoyancy acts at a point called the *centre of buoyancy*, which is the centre of gravity of the displaced liquid.

162. Specific Gravity.—A pint of mercury weighs 13.6 times as much as a pint of water. In other words, if we compare the weights of equal volumes of mercury and water, we shall find that the mercury is 13.6 times heavier than the water. This number 13.6 is called the *specific gravity* of mercury, and represents the specific or particular effect of gravity on a given volume of mercury, as compared with its effect on an equal volume of water.

A pound of water occupies a volume 13.6 times greater than that occupied by a pound of mercury. That is, gravity produces the same effect of weight on a given volume of mercury that it does on a volume of water 13.6 times greater; or, as before, the specific gravity of mercury is 13.6 times as great as that of water.

163. General Methods of Determining Specific Gravity.—There are two general methods for determining the specific gravity of a substance:

(1) By the comparison of the weights of equal volumes.

(2) By the comparison of the volumes of equal weights.

The specific gravity of solids and liquids is generally referred to pure water as a standard. That of gases and vapors is generally referred to air.

The specific gravity of a substance may be determined by a comparison of the weights of equal volumes of the substance and water as follows:

Rule.—Divide the weight of the body in air by the weight of an equal volume of water.

This may be expressed as follows, viz.:

$$\text{Sp. gr.} = \frac{\textit{Weight of body in air}}{\textit{Weight of equal volume of water}}.$$

The specific gravity of a gas is determined in the same manner, air, instead of water, being taken as the standard of reference.

In order, therefore, to determine the specific gravity of any body, it is only necessary to ascertain the weight of that body and the weight of an equal volume of water or of air.

Suppose, for example, it is required to determine the specific gravity of a piece of iron. First find the weight of the iron in air, which we will suppose to be 7780 grams. Then find the weight of an equal volume of water, which will be, say, 1000 grams. The specific gravity of the iron, therefore, is $\frac{7780}{1000} = 7.78$, or, in other words, the iron is 7.78 times heavier than water.

164. Methods of Obtaining Specific Gravity by the Balance, for Solids Heavier than Water.—Since a body immersed in water apparently loses as much weight as the weight of the water it displaces, it is easy to obtain its specific gravity by the balance; for, attach the body to a string tied to one of the pans of a balance; exactly balance the body by adding weights to the other pan; these weights will give the weight W of the solid in air. Then, while still attached to the balance, immerse the solid in water, and find the weight in water. This weight will give W'. Then W minus W' will give the loss of weight of the body when immersed, which is equal to the weight of an equal volume of water. The specific gravity is then given by the formula—

$$\text{Sp. gr.} = \frac{W}{W-W'}. \quad (26)$$

Suppose, for example, a solid weighs in air 2000 grams, and weighs in water 500 grams, then its specific gravity $= \frac{2000}{2000-500} = \frac{2000}{1500} = 1.333.$

165. Balance Method for Solids Lighter than Water.—Attach the body, such as a piece of cork, to a solid, say a piece of lead, heavy enough to sink the cork in the water. Find the weight which the two apparently lose when immersed in water. Find what weight the lead loses when immersed in water, then the difference between this weight and the weight that both lose in water, will give the weight which the cork loses in water, Divide the weight of the cork in air by the weight it loses in water, and the quotient will be the specific gravity. Suppose, for example, the cork weighs 6 grams, and that, when both are immersed in water, they lose 35 grams, also that the heavier solid, when immersed in water, loses 10 grams. The cork must lose 25 grams, and its specific gravity must equal $\frac{6}{25} = 0.24$.

166. Balance Method for Liquids.—A closed bulb *D*, Fig. 68, partly filled with mercury or other substance sufficiently dense to sink it in most liquids, is attached to a fine wire, and suspended from one of the pans of a balance. First find the weight which the bulb loses when immersed in the liquid whose specific gravity is desired. This will be the weight of a volume of liquid equal to the volume of the bulb *D;* then find the weight which the bulb *D* loses when immersed in water; this will give the weight of the volume of water equal to that of the bulb. Then divide the weight the bulb loses in the liquid whose specific gravity is desired by the weight it loses in water, and the quotient will be the specific gravity. Suppose, for example, the bulb *D* loses 18.4 grams when immersed in sulphuric acid, and 10.0 grams when immersed in water; then $\frac{18.4}{10.0} = 1.84$, the specific gravity of the sulphuric acid.

FIG. 68.

167. By the Specific Gravity Bottle.—The specific gravity of a liquid may be conveniently found by means of a bottle, which is first weighed when empty, and then filled with the liquid, say milk, whose specific gravity is desired, and again weighed; this weight, less the weight of the bottle, will give the weight of a quantity of milk that will exactly fill the bottle; the bottle is then emptied, filled with water, and again weighed. This weight, less the weight of the bottle, will give the weight of the water that will exactly fill the bottle; then the weight of the milk, divided by the weight of the water, will give the specific gravity of the milk.

Thus, suppose the bottle, when empty, weighs 25 grams, when filled with milk, 76.3 grams, and when filled with water, 75 grams; then 76.3 —25 = 51.3 grams, the weight of the milk, and 75 —25 = 50 grams, the weight of the water, and $\frac{51.3}{50.0} = 1.026$, the specific gravity of the milk.

168. By the Hydrometer.—A pound of water occupies a space 13.6 times greater than a pound of mercury. This number 13.6 is called the specific gravity of mercury.

The specific gravity of a liquid may be determined by the comparison of the volumes of equal weights.

The apparatus frequently employed for the determination of the specific gravity of a liquid is called a *hydrometer.*

One form of hydrometer is seen in Fig. 69. It is made of glass and is hollow except at its lower end, which contains sufficient mercury, or other heavy substance, to cause it to float upright when placed in any ordinary liquid. When the instrument is placed in any liquid, it will sink until it displaces a volume of liquid equal in weight to its own weight. But the denser the liquid, the less the depth to which the hydrometer will sink; for the less will be the volume of liquid required to equal in weight the weight of the instrument.

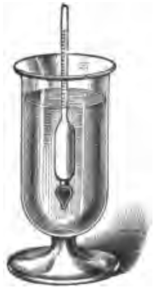

FIG. 69.—Hydrometer.

The specific gravity of any liquid may, therefore, be determined by comparing the distance to which the instrument sinks when placed in water, with the distance it sinks when placed in the liquid whose specific gravity is desired. A scale, marked on the tube, usually gives the specific gravity by direct inspection.

Instruments of this kind, when used to determine the specific gravity of milk, are called *lactometers;* and of alcohol, *alcoholometers.*[1]

Since the weight of a cubic foot of water = 62.4 lbs. avoir., if we know the specific gravity of any substance, we can easily calculate the weight of a cubic foot of that substance; thus, the sp. gr. of gold = 19.30; then a cubic foot of gold = 19.30 × 62.4 = 1204.32 lbs. So, also, if we know the weight of a body and its specific gravity, we can calculate its volume. Thus, what is the volume of 100 lbs. of gold? Since one cubic foot of gold has a weight of 1204.32 lbs., 100 lbs. must occupy the $\frac{100}{1204.32}$ of a cubic foot = 0.08303 cubic foot.

Again, since one cubic centimetre of water equals one gram, the weight in grams of 1 c.c. of any substance will be equal to its specific gravity; thus, the weight of 1 c.c. of mercury is 13,595 grams.

These relatives are expressed by the formulas

$$d = \frac{m}{v};\ m = dv;\ v = \frac{m}{d}; \quad (27)$$

where d = density, m = mass, and v = volume of the substance.

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[1] In the following table, the specific gravity of a few common substances will be found. It should, however, be remembered that the specific gravities vary slightly with different specimens of the same substance.

Solids

Iron (wrought)	7.86
Zinc	7.15
Lead	11.37
Copper	8.92
Silver	10.53
Gold	19.32
Platinum	21.50
Granite	2.66
Ice	.93
Cork	.24

Liquids

Mercury	13.595
Sulphuric acid	1.840
Milk	1.030
Ocean water	1.026
Alcohol	.792
Ether	.736

PROBLEMS

1. A reservoir is filled with water to a depth of 50 feet. What is the pressure, in lbs. per square inch and in grams per square centimetre, on the bottom of the reservoir, in excess of the pressure of the atmosphere?

2. The Pacific Ocean is in some places 4000 fathoms; *i. e.*, 24,000 feet deep. What is the pressure at the bottom in excess of the pressure of the atmosphere, in lbs. per square inch and in grams per square centimetre.

3. In the case of the last example, suppose a corked empty glass bottle to be so loaded as to sink to the bottom of the ocean. If the neck of the bottle has an internal cross-sectional area of 3 square centimetres, what will be the total pressure on the cork tending to drive it into the bottle, in kilograms weight?

4. An empty tumbler has 100 cubic centimetres of ice placed in it, and is then completely filled with water, so that the tumbler is not only full to the brim, but the floating ice projects above the surface. When the ice has all melted, how much water will have overflowed from the tumbler? and why?

5. A log of wood has a volume of 100,000 cubic centimetres and weighs 70 kilograms. How much weight in grams will be required to just sink the log in fresh water?

6. A loaded boat weighing in air 20 tons of 2240 lbs. is floated in fresh water. How much water in lbs. weight, in cubic feet, and in cubic centimetres will it displace?

7. If the same loaded boat be floated in sea water of specific gravity 1.026, how much water will it displace in lbs. weight, in cubic feet, and in cubic centimetres?

8. A stone has a volume of 80,000 cubic centimetres, and has a mass of 240 kilograms. What is its specific gravity?

9. The standard pressure of the atmosphere at sea level is usually considered as being equal to that of a column of pure mercury at 0° C., 760 millimetres in height. Taking the specific gravity of mercury as 13.595, what would be the height in feet

and in centimetres of the corresponding column of pure water?

10. A specimen of metal weighs 120 grams in air, and 106.5 grams in water. What is the specific gravity of the specimen?

11. If 5.5 cu. ft. of iron weigh 2700 lbs., what is the specific gravity of the metal?

12. A specific gravity bottle which weighs 55 grams, weighs 105 grams when filled to the mark with water and 147 grams when filled with an acid. What is the specific gravity of the acid?

13. Compute the specific gravity of wax from the following data: Weight of wax in air, 20 grams; weight of sinker, 210 grams; weight of sinker in water, 191.4; weight of both in water, 188.94.

14. In the above problem what is the volume of the sinker? What is its density? What metal is it? What is the volume of the piece of wax?

15. A glass bulb weighs 14.326 gr. in air and 8.926 gr. in water. When immersed in nitric acid it weighs 6.658 gr. What is the specific gravity of the acid?

16. A piece of metal weighs 20.4 gr. in air, 14.4 gr. in water, and 14.94 gr. in oil. What is the sp. gr.—(*a*) of the metal? (*b*) of the oil? (*c*) What is the volume of the metal?

17. There is a uniform rod 6 ft. long and 4 in. square of sp. gr. 0.5. What must be the sp. gr. of a cube of metal 4 in. on a side, which, when attached to the lower end, will submerge the rod in water?

18. A cubical block of wood 2 cm. on a side weighs 5 gr. How far will it sink in alcohol of sp. gr. 0.8?

19. The sp. gr. of a certain substance is 8. Ten c.c. of this substance are attached to a body which weighs 20 gr. in air. Both together weigh 50 gr. when submerged in water. What is the sp. gr. of the body?

20. A cylindrical rod 3.5 m. long weighs 12.5 kg. in air and 2 kg. in water. Find the radius of the rod and the sp. gr. of the substance.

CHAPTER IX

HYDRAULICS

169. **Hydraulics** treats of liquids in motion. It describes the flow and elevation of liquids, and the machines for moving liquids, or intended to be moved by them.

170. **Escape of Liquid from Orifices in Containing Vessels.**—The walls of a vessel filled with liquids are subjected to two pressures:

(1) The pressure of the liquid directed outward, from within.

(2) The pressure of the air directed inward, from without.

If a hole be pierced in a side of a vessel containing a liquid, the liquid will escape only when the pressure from within is greater than the atmospheric pressure. If the vessel be open at the top, so as to permit the pressure of the air to act on the upper surface of the liquid, the liquid is pushed out of the orifice by the pressure of the air, with the same force as that with which it is pressed in. The liquid, therefore, tends to run out with a force equal to the pressure caused by the depth of the liquid above the opening; or, in other words, the effect of atmospheric pressure is eliminated.

Water flowing from a narrow-necked bottle does not escape in a steady stream, but at more or less regular intervals partially stops flowing, until a few bubbles of air enter the neck of the bottle with a gurgling sound, when the flow again begins. The partial stoppages are due to the pressure of the atmosphere, which occasionally forces bubbles of air into the bottle against the pressure of the escaping liquid. The air thus forced into the bottle occupies the space left by the liquid which has escaped. After a certain quantity of the liquid has escaped, the pressure of the air against the mouth of the bottle becomes greater than the pressure forcing the liquid out. More air then enters, and more liquid escapes. Were a hole made in the bottom of the bottle, the liquid would escape in a steady stream.

171. Theorem of Torricelli.—If an opening or orifice be made at the middle point *c* of a vessel filled with water, and also at *a*, *b*, *d*, and *e*, at equal distances above and below *c*, and the water be permitted to escape in a horizontal direction, then the greater the distance of the orifice below the surface of the water, the greater will be the velocity with which the water will flow from the vessel.

If an opening provided with a vertical jet be made at *j*, exactly opposite *e*, then the velocity with which the water escapes at *j* may be determined by the height reached by the jet. This may be taken as approximately the vertical distance *j A*; for, disregarding the resistance of the air, the initial velocity of a body thrown upward to a given vertical distance is equal to the velocity the body would acquire in freely falling through that distance. Therefore, the water escapes at *j* with the same velocity it would acquire in falling through the vertical distance *j A*, called the *head*.

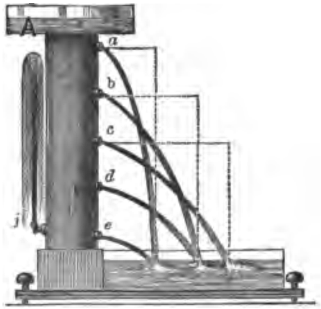

FIG. 70.—Torricelli's vase.

But the velocity in feet per second, acquired by a body falling through a given distance is equal, approximately, to eight times the square root of that distance in feet (more nearly 8.02). Or, since this distance is the head, the velocity in feet per second will be 8.02 multiplied by the square root of the head in feet.

$$V = \sqrt{2as} = \sqrt{2a}\sqrt{S} = \sqrt{2 \times 32.16}\sqrt{S} = 8.02\sqrt{S}.$$

The velocity, therefore, varies directly as the square root of the head.

This principle was discovered by an Italian philosopher named Torricelli, and is generally known as Torricelli's theorem.

Torricelli's theorem may be expressed as follows:

Liquids flow from an orifice in a containing vessel with the velocity they would acquire in falling freely from the level of the liquid to the centre of gravity of the orifice.

Suppose, for example, that the orifice was four feet below the surface of the liquid; then the velocity of escape would be $8.02 \times \sqrt{4} = 8.02 \times 2 = 16.04$ feet per second.

172. Method of Ascertaining the Flow.—

Experiment 33.—Bore three small holes of the same size in the side of a tin can, one near the bottom, one near the top, and the third midway between the two. Fill the can with water and note the quantity that escapes in the same time from each of the three openings. Observe that the flow from the lowest hole is greatest and that from the upper hole is least. In order to avoid the effects produced by change of level, keep the can filled with water by pouring in water constantly.

The *flow*, or amount of liquid escaping from an orifice in a given time, may be ascertained by multiplying the velocity with which the water comes out of the orifice, by the area of the orifice and by the number of seconds it continues to flow.

The area of the orifice multiplied by the velocity must give the rate of flow; for, if the area of the orifice is one square inch, and the velocity of the escape twelve inches per second, then, in one second, a mass of water one inch in area of cross-section and twelve inches long would flow out of the orifice, the volume of which would, of course, be twelve cubic inches. Since the velocity of escape from any vessel varies with the head of the liquid, and this decreases as the liquid runs out, the quantity discharged from any given orifice must be greater during the first second than during the second, and greater during the second second than during the third, and so on. We cannot, therefore, ascertain the quantity discharged in, say, 60 seconds, by multiplying the quantity discharged during the first second by 60, unless the head is kept constant by allowing water to run into the vessel as fast as it runs out.

173. The Flow of Liquids through Horizontal Pipes.—When a liquid flows through long pipes, such as the water-pipes of a city, the friction of the water against the sides of the pipes greatly diminishes the velocity of flow. This is especially the case at the bends of the pipe, where the liquid is forced suddenly to change the direction of its motion. It is on account of this decrease in velocity that water must be put under considerable pressure to cause a sufficient volume of liquid to flow through long pipes in a given time.

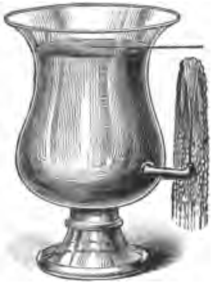

FIG. 71.—Height of jet.

174. Vertical Jets.—A jet of water escaping vertically upward from a reservoir does not actually rise as high as the level of the water in the reservoir, because—

(1) Its velocity is diminished by friction against the sides of the orifice.

(2) Some of its motion is lost in pushing the air out of the way.

(3) The falling water strikes the water which is rising, and so decreases its velocity.

175. Reaction of an Escaping Jet.—When a jet of liquid is escaping from an orifice in a vessel, it will produce a pressure which, if the vessel is free to move, will cause it to move in a direction opposite to that in which the liquid is escaping. Suppose, for example, the vessel *A*, Fig. 72, has, at its lower end, a horizontal tube *C*, the ends of which are bent as shown. As the liquid escapes from openings at the extremities of this tube, the vessel rotates in a direction opposite to that in which the liquid is escaping.

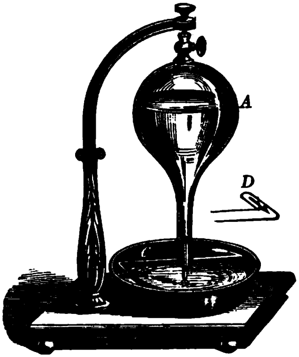

FIG. 72.—Reaction vase.

The cause is as follows: Were the openings at the ends of the tube closed, the pressures on directly opposite portions of the wall, being equal and opposite, would neutralize each other. But when the liquid begins to run out of an opening, the pressure at this point is removed, and the pressure on the opposite side, being no longer neutralized, moves the vessel around. The direction in which this pressure acts is shown at D. This effect produced by the escaping liquid is called the *reaction of the escaping jet.*

The amount of the pressure produced by the reaction of the escaping jet is equal to twice the pressure on the orifice produced by the liquid when at rest.

176. Water-wheels.—The moving water in a river possesses a considerable amount of energy. We may utilize this energy and cause it to do useful work; *i. e.*, to act as a *water power*, by permitting the moving water to impart its motion to a water-wheel.

The commercial applications of water power are rapidly increasing. Now that the developments of electricity have rendered the transmission of power more economical, the utilization of the energy of rivers is becoming quite common. Of the enormous energy of the Niagara River at Niagara Falls (about 7,000,000 horse-power), a part is already being utilized by electrical transmission.

177. Energy Transferred from Running Water to Wheels.—There are three ways in which the energy of motion of a running stream may be transferred to a water-wheel:

(1) By *impact.* The moving water is caused to strike float-boards or buckets placed on the wheel and so to drive it.

(2) By *weight.* The wheel is provided with buckets so shaped as to hold the water as far as possible on one-half of the vertical diameter, and thus, by making that side heavier than the other, to drive the wheel.

(3) By the *reaction of the escaping jet.* The buckets are so shaped as best to permit the force of the escaping jet to drive the wheel.

178. The Undershot Wheel.—In the undershot water-wheel, the water strikes near the bottom of the wheel, against a number of flat boards called *float-boards*, placed as shown in Fig. 73.

This wheel is moved mainly by the impact or blow produced by the moving water striking the float-boards.

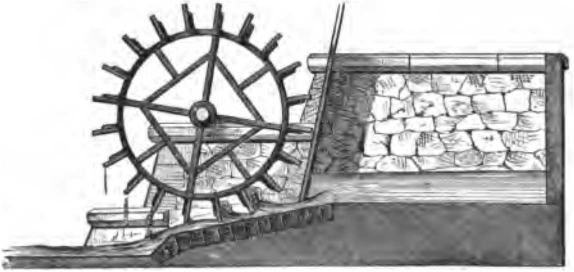

FIG. 73.

179. The Overshot Wheel.—In the overshot wheel the water is received at the top of the wheel by buckets, shaped as shown in Fig. 74, so as to retain a large proportion of the water until it

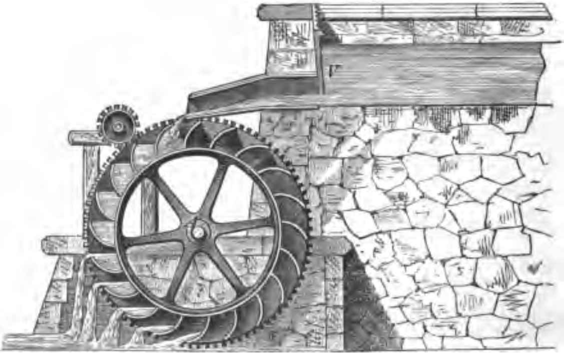

FIG. 74.

reaches the lowest point. The wheel is moved by the momentum of the moving water and by the weight of the water in the buckets, that side of the wheel which receives the water being heavier than the opposite side.

180. The Breast Wheel.—In the breast wheel the water is received on the wheel at or near the level of the axis A, as shown in Fig. 75. The buckets are placed perpendicularly to the circumference of the wheel, and are arranged so as to hold the water until they reach the lower point, which is done by causing the ends of the buckets to move near the curved waterway down which the water runs. The breast wheel is turned both by the impact and the weight of the water.

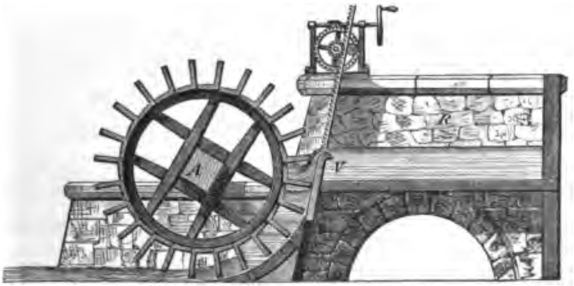

FIG. 75.

181. The Turbine Water-wheel.—In the turbine water-wheel, advantage is taken of the reaction of the escaping jet.

Fig. 76 represents one form of turbine in perspective and in horizontal section. The wheel is so placed that the water may readily escape from the wheel after it has given motion to it.

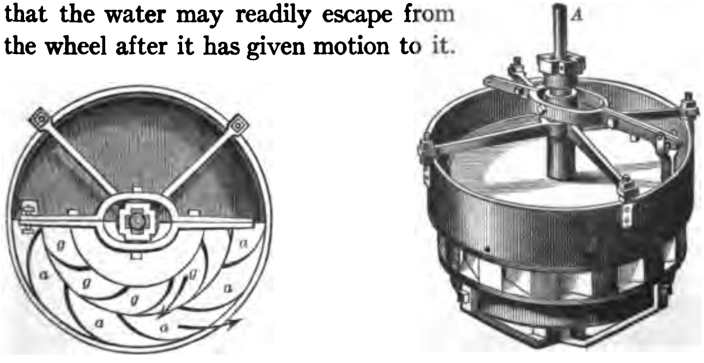

FIG. 76.

The top of the wheel is covered, to protect it from the direct pressure of the water. The movable part of the wheel is seen at *a*, *a*, *a*, *a*, which is attached to the shaft *A*. The water enters below, through openings between fixed curved guides *g*, *g*, *g*, *g*, so inclined to the buckets that, on leaving the guides, it strikes the buckets in the most advantageous direction. The wheel is driven partly by the momentum of the moving water and partly by the weight of the water in the buckets. But this is not all; on running out of the buckets the reaction of the escaping stream also aids in turning the wheel. The turbine water-wheel is now largely used to make water-power available for generating electric currents. A closely related application of the reaction jet is that of the steam turbine, as used to propel ships.

PROBLEMS

1. A cubical vessel is filled with water; how much greater is the pressure on the base of the vessel than on any of its vertical sides?

2. A tank 9 feet deep is filled with water. If an opening is made in the side of the tank at the bottom, with what velocity will the water commence to escape?

3. If the opening in the preceding problem has a cross-sectional area of 2 square centimetres and the velocity is uniform over the entire cross-section, what will be the flow of water escaping from the tank in the first ten seconds, in cubic centimetres?

4. A city water-pipe carries water at a pressure of 70 lbs. per square inch above that of the atmosphere. (1) What elevation or head of water does this pressure correspond to in feet? (2) If an opening be made in the upper side of the pipe, how high, in feet, will the water rise in the issuing jet, assuming the pressure in the pipe to be sustained?

5. A large iron tank filled with water has three openings cut in its side, the first four feet, the second nine feet, and the third sixteen feet below the surface of the water. What will be the velocity of flow from these three openings in feet per second?

CHAPTER X

PNEUMATICS

182. Properties of Gases.—A bladder or rubber bag partly filled with air is tied at the neck and placed under a bell-jar connected with an air-pump. As the air is removed from the bell-jar, the air in the bladder being relieved of the pressure of the air upon it, at once expands and fills the bladder. If now the air be allowed again to enter the bell-jar, the air in the bladder at once returns to its former volume.

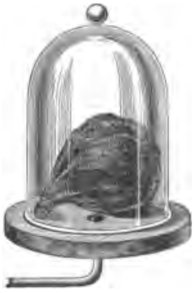

FIG. 77.

A characteristic property of a gas is, therefore, its expansibility. Whenever it is possible for it to do so, a gas immediately expands into and fills any space in which it may be put. If a small amount of a gas with a powerful odor, such as chlorine or ammonia, is permitted to escape into a room, it is soon easily detected in all parts of the room. If more of a gas is forced into a vessel than it has held before, the pressure of the gas is increased.

183. Kinetic Theory of Gases.—All these properties of gases are explained by assuming that the molecules are in rapid motion. The pressure on the walls of the containing vessel is due to the impact of the molecules. If the gas is warmed, the velocity becomes greater, the number of hits in a given time increases, and, therefore, the pressure increases. If the pressure on the bladder is removed, the molecules inside tend to distend it until the bombardment on both sides is equal. If a gas is released in one corner of the room, it does not stay there, since the molecules can move to the other parts of the room. Calculations have proved that the average velocity of the molecules of hydrogen is equal at 0° C. to about 1844 metres per second.

184. Pressure of Gases.—When permitted to act, the pressure of a gas causes it to expand or increase in volume. If not permitted to cause an increase in volume, it is exerted against the walls of the containing vessel. In the case of air and other gases on the earth's surface, the tendency to expand is held in check by gravity, as was proved in paragraph 182.

This tendency of a gas to expand on the relief of pressure often causes a balloon to burst as soon as it reaches a certain elevation in the air. To avoid this, a valve is placed in the top of the balloon to enable the aeronaut to let out gas and thus relieve the internal pressure when necessary.

185. The Atmosphere, the name given to the mass of air which surrounds the earth, consists of a mechanical mixture of two gases, oxygen and nitrogen, in the proportion, by volume, of about one part of oxygen to four of nitrogen. The atmosphere contains also a small quantity of carbonic acid and a variable quantity of the vapor of water, and about one per cent. of an inert gas, argon.

The atmosphere is kept in its place by the force of gravity; it is densest at the earth's surface at the level of the sea, and becomes rarer as we ascend, being, for example, rarer at the summit of a mountain. If all the air had equal density, it would be contained in a layer or ocean 26,000 feet in depth; but, owing to its diminishing density, the upper limit is at a far greater distance above the surface.

186. Diffusion of Gases.—

Experiment 34.—Pour equal volumes of mercury, water, and oil into a tall jar. Observe that no matter how thoroughly they may be shaken together, if allowed to stand, they will soon separate into distinct layers according to their differences of density, the mercury being the heaviest, falling to the bottom of the jar, the oil floating on top, and the water occupying an intermediate position.

All liquids, however, will not thus separate into layers when mixed together; many possess the power of diffusing, or mixing through each other, notwithstanding their differences of density, so that a heavier liquid will rise and diffuse through, or mix with, a lighter liquid placed on top of it. This mixing of liquids notwithstanding differences in density is called *diffusion.*

Gases possess the power of diffusion in a marked degree. If a light gas be placed in the upper part of a vessel, and a heavier one in the lower part, the two will not remain separate, even if the vessel be kept still. The heavy gas will rise and the light gas will fall, until they have become evenly mixed or diffused.

Diffusion of gases can be readily explained by the kinetic theory of matter. The molecules of each gas, in their motions, readily move into the intermolecular spaces of the other gas, and so eventually effect a thorough admixture.

The property of diffusion is of great utility in our atmosphere, in keeping the oxygen, nitrogen, and carbonic acid gases thoroughly mingled. Were these gases to settle in separate layers according to their differences in density, the life which now exists on the earth would either entirely cease or be greatly modified. By the property of diffusion, we find relatively the same general proportion of the heavier gases in the air over the summits of high mountains as in the lower layers near the earth.

Diffusion of gases takes place also through porous partitions. Here the rapidity of diffusion varies with the size of the pores and with the size of the molecules of the gas; *i.e.*, with the kind of gas.

The gradual collapse or shrinkage of a toy gas-balloon is due to the loss of its contained hydrogen by diffusion into the air.

Experiment 35.—The diffusion of gases through a porous partition is readily shown as follows. Fasten a cork into the mouth of an unglazed porous cup and fit into the cork a long glass tube. Arrange the cork so that the tube points downward and dips into a vessel of colored water. Fill a small bell-jar with hydrogen or with illuminating gas and quickly place it over the porous cup (Fig. 78). The hydrogen passes into the porous cup more rapidly than the air passes out and, therefore, so increases the pressure in the porous cup that bubbles of air are forced out through the liquid. If the bell-jar is now removed, the hydrogen escapes more readily than the air can enter, producing a reduced pressure. The atmospheric pressure upon the surface of the water in the vessel, therefore, forces some of the colored water up the tube. In a few seconds this begins to fall as the pressure in the porous cup gradually adjusts itself to equilibrium.

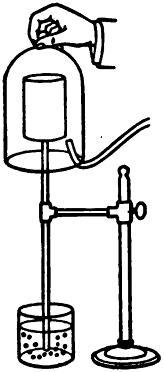

FIG. 78.—Diffusion.

187. Atmospheric Pressure.—Since we live at the bottom of an ocean of air, we must, like everything else at the earth's surface, sustain a pressure arising from the weight of the air above us. Gases, however, like liquids, transmit pressure equally well in all directions, and the equal and opposite pressures so neutralize each other that we do not feel the pressure which the air exerts on us. When, however, the pressure is removed from one side, the pressure on the other side is at once manifested.

The air presses so equally on all sides of bodies that it was long before the existence of an atmospheric pressure was discovered. This pressure was first measured in 1643 by Torricelli.

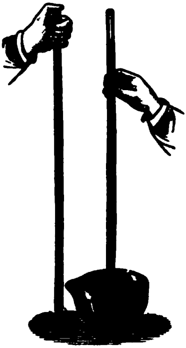

FIG. 79.—Barometer.

188. Torricelli's Experiment.—Torricelli's famous discovery was made by means of the following experiment: A glass tube about 33 inches long, closed at one end, was filled with mercury. Placing his thumb over the open end, as in Fig. 79, he inverted the tube and dipped the open end below the surface of mercury in a cup. When the thumb was taken away, the mercury did not all run out of the tube, a column about 30 inches high remaining in the tube, where it was kept by the pressure of the air on the mercury in the cup.

The atmosphere, by its weight, exerts a downward pressure on the surface of the mercury in the cup; but the upward pressure against the open mouth of the tube is equal to the downward pressure; *therefore, the total pressure which holds the mercury in the barometer is equal to the weight of a column of air of the same area of cross-section as the column of mercury in the tube, and extending upward from the level of the mercury in the cup to the upper limit of the atmosphere.*

At the level of the sea, the pressure of the atmosphere will hold up a column of mercury about 30 inches (762 mm.) in height above the level of the mercury in the cup. If the area of the open end of the tube be one square inch, this column of mercury will weigh about fifteen pounds. *Therefore, the pressure of the atmosphere at the level of the sea is about equal to* 15 *lbs. to every square inch of surface, or about one kilogram to the square centimetre of surface.*

The calculation is made as follows: If the height of the mercury column is 76 cm., and its cross section is one sq. cm., the volume is 76 cubic centimetres. If this were water, it would weigh 76 grams, but since the density of mercury is 13.569, the weight of the mercury is 1033.3 grams. As 76 cm. is the average height of the barometer at sea-level, this shows that the pressure of the atmosphere equals 1033.3 grams per square centimetre.

189. The Barometer.—Torricelli's tube forms an instrument called the *barometer*.

The barometer may be regarded as a species of air-balance. The weight on one arm of the balance is a column of air reaching from the level of the mercury in the cistern to the upper limits of the atmosphere; the weight on the other arm is that due to the column of mercury in the tube. Any variation in the pressure of the atmosphere causes a corresponding variation in the height of the mercurial column in the barometer.

By means of a barometer we may note the variations that occur in the pressure of the atmosphere. If, from any cause, the atmospheric pressure increases, the mercury rises in the barometer tube; if the pressure decreases, the mercury falls. As a rule, a rise of the mercury in the barometer is followed by clear weather, its fall by foul weather. The barometer is used, both on land and sea, to observe approaching changes in the weather. Its use, however, for this purpose requires considerable experience.

Since it is only the air above the mercury in the cup that keeps the mercury in the tube, it follows that if we carry a barometer up a high mountain, the mercury in the tube will fall as we ascend. The barometer, therefore, may be used *to measure the height of mountains or other elevations.*

Barometers may be made with other liquids than mercury; the height of the column will depend on the density of the liquid. Thus, if water be used, the height will be about 34 feet; for, since mercury is about 13.6 times heavier than water, the height would be 13.6 × 30, or 408 inches, or about 34 feet, were it not for the fact that the vapor of water formed in the tube would somewhat decrease the height.

190. The Aneroid Barometer is a barometer that does not contain any liquid. This barometer depends for its operation on the pressure exerted by the air against the surface of a short, cylindrical box, of thin elastic metal, partially exhausted of air. An increase in the pressure of the air causes the box to collapse partially; *i. e.*, the top and the bottom of the box move toward each other. On a decrease in pressure the elasticity of the metal causes the top and bottom to move away from each other. These changes cause a needle to move over a graduated scale. The general arrangement of the parts of an aneroid barometer is shown in Fig. 80.

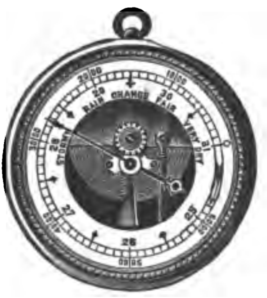

FIG. 80.—Aneroid.

191. Pressures Expressed in Atmospheres.—It is convenient to express the pressure exerted by a column of liquid or gas in units of pressure called *atmospheres*. Thus, a pressure equal to 15 lbs. per square inch is called a pressure of *one atmosphere;* a pressure of 60 lbs. to the square inch is called a pressure of *four atmospheres*, and so on.

192. The Air-pump.—In order to demonstrate the pressure which the atmosphere exerts on any object, it is necessary to remove the pressure of the air from one side of the object. This is most conveniently done by means of an apparatus called an *air-pump*.

Fig. 81 represents a form of air-pump. An air-tight piston *P* moves in the cylinder *C*. Openings are provided at *a* and *c*, in the bottom and top of the cylinder, and at *b* in the piston. These openings are alternately shut and opened by contrivances called *valves*. In the air-pump these valves all open upward. The cylinder is connected by a tube *e*, with a flat plate *M*, on which is placed a glass vessel *R*, called the *receiver*, the base of which is carefully ground so as to insure an air-tight joint. By successive movements of the piston, the air in the receiver *R* is gradually removed, when the receiver is said to be *exhausted*.

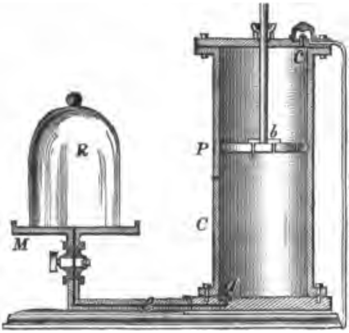

FIG. 81.

The operation is as follows: When the piston rises, say from the bottom of the cylinder, a vacuum is left below it, into which some of the air from the receiver *R*, at once passes, lifting by its pressure the valve *a*. When the piston descends, the air in *C* is compressed, the valve *a*, shut, and the valve *b*, opened, and the air below the piston is transferred above it. As the piston again rises, more air passes from *R* to the cylinder, while the air above the piston is forced out of the cylinder through the opening *c*.

193. Illustrations of Atmospheric Pressure.—The glass receiver *R* may easily be lifted from the plate of the air-pump when not exhausted. But when the receiver is exhausted, the pressure of air on the outside holds it so firmly to the plate that, if the receiver is moderately large, it will be almost impossible for an ordinarily strong person to remove it from the plate until the air is again allowed to enter.

Two hollow hemispheres of brass, provided with smooth plane edges, if simply pressed together, so as to form a hollow sphere, and then connected with an air-pump so that the air may be removed from the inside, are held together so firmly by the pressure of the air on the outside that it is difficult to pull them apart.

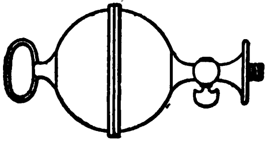

FIG. 82.—Magdeburg hemispheres.

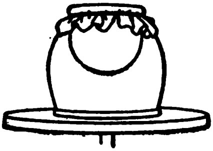

FIG. 83.—Bladder glass.

When a receiver with an open top, over which a piece of bladder has been tightly stretched, is placed on the plate of an air-pump and exhausted, the pressure of the air on the bladder bursts it with a loud report.

194. Simple Experiments in Atmospheric Pressure.—The following experiments in atmospheric pressure can be shown without the use of an air-pump.

Experiment 36.—Place the open end of a hollow key to the mouth, and, after vigorously sucking out the air, quickly press the end against the lip. Observe that the key will be held there by the pressure of the air.

Experiment 37.—Select a small wineglass with a smooth edge. Place some small pieces of tissue-paper loosely under the glass, and set fire to them. As soon as they are nearly consumed, quickly press the glass against the hand. Observe that it will then be held against the hand with considerable force. The heat expands the air and drives part of it out of the glass, which, on cooling, is then held against the hand by the outside atmospheric pressure.

Experiment 38.—Fill a smooth-edged tumbler with water; place a piece of stout paper over the top, and, holding the palm of the hand against the paper, slowly invert the tumbler. Though the hand be now removed from the paper, the water will not run out, because the pressure of the air holds the paper firmly against the tumbler, as shown in Fig. 84.

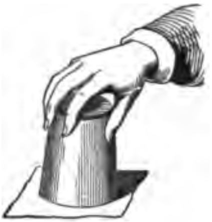

FIG. 84.

Experiment 39.—Select an empty tomato can, from the top of which the small round piece of tin has been removed, leaving an opening about two inches in diameter. Tie a piece of mosquito-netting firmly around this end of the can, stretching it smoothly over the top with the fingers. Fill the can with water and place a piece of smooth, stiff paper over the open end, and invert, as in the previous experiment. Observe that the paper will then be held against the can by the pressure of the air. Now, holding the can as shown in Fig. 85, cautiously slide the paper from the netting, *and the water will still remain in the can, although the open end is only protected by the mosquito-netting.*

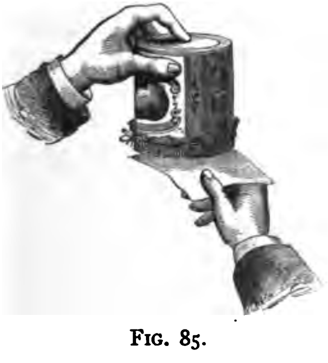

FIG. 85.

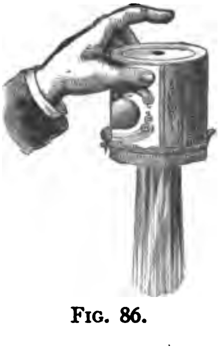

FIG. 86.

Experiment 40.—Prepare a can as described in Experiment 39, and punch a hole with a nail in the bottom of the can. Holding a finger firmly over the hole, fill, invert, and remove the paper as before, and the water will not run out; now remove the finger momentarily from the hole, as shown in Fig. 86, and observe that the pressure of the air being then exerted downward on the water, as well as upward, the water flows out by its own weight. Replace the finger, and the flow ceases, since the pressure of the atmosphere is greater than the weight of the water. This curious experiment proves (1) Atmospheric pressure; (2) adhesion of water to the netting, and (3), cohesion of the molecules of the water.

The common leather sucker depends for its operation on the pressure of the air.

195. Buoyancy of Air.—The Law of Archimedes.—A body weighed in air loses weight equal to the weight of the air it displaces. For ordinary purposes this loss of weight may be disregarded; but it becomes more appreciable as the bulk of the thing weighed exceeds the bulk of the weights used to balance it.

Suppose, for example, that a pound of feathers be balanced in air by a pound of lead; then, since the bulk of the feathers is greater than that of the lead, the buoyancy of the air must decrease the weight of the feathers more than it does the weight of the lead, *and, therefore, more than one pound of feathers is required to balance one pound of lead in air.*

196. Balloons.—A solid, lighter than water, when completely immersed in water, unless held in place, will rise until it floats, with a certain portion only of its mass below the water. It rises because when completely immersed it is thrust upward by the force of buoyancy, which is then greater than its weight.

Balloons rise through air for the same reason; for, being filled with some light gas or heated air, their weight, which tends to pull them down, is less than the buoyant force of the displaced air which tends to push them upward. When these two forces are exactly equal, the balloon will neither rise nor fall. *The ascensional* or *lifting power* of a balloon can, therefore, be found by subtracting the weight of the balloon, enclosed gas, and car from the weight of an equal bulk of air.

At the sea-level, and at ordinary temperature and pressure, 100 cubic inches of air weigh about 31 grains; or 1 cubic centimetre of air at 0° C. and 760 m.m. pressure weighs 0.001293 gram.

197. Boyle's or Mariotte's Law.—Effect of Pressure on the Volume Occupied by a Gas.—Gases, as we have seen, are the most compressible forms of matter. As the pressure on any bulk of gas is increased, its volume is diminished; conversely, as the pressure is decreased, the pressure of the gas causes its volume to increase. The law according to which these changes occur was discovered independently by Boyle and by Mariotte, and may be expressed as follows:

At the same temperature, the volume occupied by a given mass of gas is inversely proportional to the pressure it supports.

This may be expressed by the proportion—

$$P : P' :: V' : V. \quad (28)$$

Where P is the pressure when the volume is V and P' the pressure when the volume is V'. Since by the above $P\ V = P'\ V'$ we see that the product of the pressure and volume remains a constant; or, $P\ V = K$.

This law is nearly true for all gases.

Suppose, for example, that a certain quantity of air, at the ordinary pressure of the atmosphere, occupies the volume of one litre; then, if the pressure on this quantity of air be increased to two atmospheres, its volume will be reduced to one-half litre; if the pressure be increased to three atmospheres, its volume will be reduced to one-third of a litre; if to ten, or one hundred atmospheres, to $\frac{1}{10}$ or $\frac{1}{100}$ of a litre. Again, if the pressure of one atmosphere on the litre be reduced to one-half an atmosphere, the pressure of the air will cause it to expand to two litres; if it be reduced to $\frac{1}{100}$ of an atmosphere, it will expand to one hundred litres. *The ability of a gas to expand on the relief of pressure appears to be unlimited.*

198. Experimental Verification of Boyle's Law.—A glass tube *h*, bent as shown in Fig. 87, is closed at *l'* and open at *h;* mercury is poured into the tube at *h* until the level is the same in both tubes, as, for example, at *l a*. The air in the closed space above *l* is then at the pressure of one atmosphere. If, now, mercury be poured in the open end at *h*, until the air in the space above *l* is reduced one-half in volume, say, until the level in the short arm is at *a′*, then the length *h′a′* will be found to be the barometric height, or sensibly 30 inches. An additional pressure of one atmosphere due to the 30 inches of mercury has, therefore, been added to the pressure of the air, making two atmospheres, and these two atmospheres of pressure have reduced the volume of the air to one-half its volume at one atmosphere.

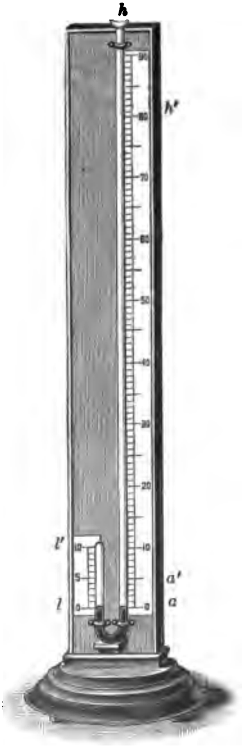

FIG. 87.—Boyle's law apparatus.

Boyle's law may be proved for pressures less than one atmosphere as follows: Cut a glass tube about 75 cm. long, open at both ends (Fig. 88). Make three file marks on it as follows: one 10 cm., a second 20 cm., and a third 58 cm. from one end. Plunge the tube into a longer tube of mercury until the 10 cm. mark is just at the level of the mercury. Close the upper open end tightly with the finger and raise the tube until the mercury has fallen to the 20 cm. mark. This means that the volume of the confined gas has expanded to twice its former amount. The mercury in the outer tube will be found to be at the 58 cm. mark. The original pressure on the confined air was measured by a column of mercury 76 cm. high. The new pressure is measured by a column 38 cm. high. The volume has been doubled while the pressure has been halved.

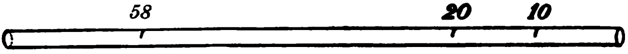

FIG. 88.

199. Effect of Pressure on Specific Gravity or Density.—Since the mass of a gas remains the same, however its volume may be changed, *the density must be proportional to the pressure.*

Thus if, under a pressure of one atmosphere, the density of a gas be 1, then under a pressure of two atmospheres, since its volume becomes $\frac{1}{2}$, its density becomes 2, and so on.

Since the lower layers of the atmosphere sustain the weight of the upper layers, the density of the air near the sea-level is greater than that at the top of a mountain.

200. Apparatus Depending for its Action on Atmospheric Pressure.—In the following apparatus advantage is taken of the pressure of the atmosphere:

1. *The Siphon.*—The siphon consists of a tube bent as shown in Fig. 89. When the shorter arm is placed below a water-surface, and the tube exhausted of air by the suction of the mouth applied at *b*, the pressure of the air on the water in *m* causes the water to rise through the height *m n*, and to flow out of the open end *b*. The greater the difference of level *a b*, between the water surface *m* and the open end *b*, the greater the velocity with which the water escapes.

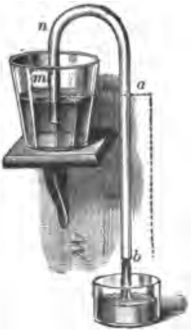

FIG. 89.

The action of the siphon may be more fully explained as follows: Suppose the distance *m n* is 10 cm., *n b* is 30 cm., and that the cross-section of the tube is 1 sq. cm. The upward pressure of the atmosphere tending to force water up the tube *m n* is 1033 grams. The weight of the water in the tube *m n* is 10 grams, since its volume is 10 cu. cm. Therefore, the difference tending to produce motion is 1023 grams. The weight of the water in the tube *n b* is 30 grams, since its volume is 30 cu. cm. Therefore, the pressure tending to force water up the tube *n b* is 1003 grams. The difference between these two is 20 grams, which, therefore, represents the pressure forcing water over from *m* to *b*. This difference is equal to the weight of the water in the tube *a b*.

2. *The Suction-pump for Raising Water.*—In the common suction-pump, Fig. 90, water is raised from a well into the body of the pump by the pressure of the atmosphere. In its simplest form this pump is essentially the same as the common air-pump. The valves open upward; one or more of these valves, *b b*, are placed in the piston, and one, *a*, at the lower end of the cylinder, or pump-barrel. As the piston is raised, a vacuum is left below it in the pump-barrel, into which the air rushes from the pipe dipping down into the well *W*. As the air is thus sucked out of the pipe, the pressure of the air on the water in *W* forces it up through the valve *a*. As the piston descends, the valve *a* closes, the valves *b b* open, and the water passes above the piston. When the piston is again raised, the water escapes at the mouth of the pump at *D*. In the figure, the valves are represented in the position they would occupy in the up-stroke of the piston.

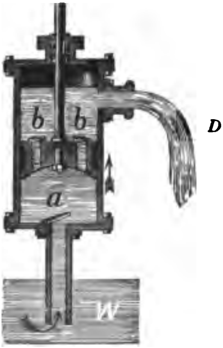

FIG. 90.

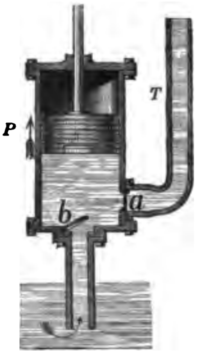

FIG. 91.

3. *The Force-pump.*—In the force-pump, Fig. 91, there is no valve in the piston *P*. A pipe *T*, enters the side of the cylinder near the bottom. A valve *a*, which opens outward, is placed where this tube enters the cylinder. There is, as in the suction-pump, a valve *b* at the lower end of the pump-barrel. On the downward stroke of the piston the water, instead of passing

above the piston, is forced through the valve *a* up through the pipe *T*. In the figure the valves are represented in the positions they would occupy during the up-stroke of the piston.

The height through which the water is raised by the pressure of the air in the siphon, the suction-pump, or the force-pump, can never exceed about 34 feet, since, as we have seen, a column of water of this height exerts a pressure equal to that of the atmosphere. In practice, pumps seldom raise water higher than 28 feet from the level of the well to that of the lower valve.

PROBLEMS

1. If the back of the hand has an area of about 28 sq. in., what force in pounds weight and in kilograms weight would be necessary to lift the hand against the pressure of the atmosphere if the pressure were entirely removed from the lower surface of the hand?

2. If a barometer tube is filled with glycerine, the specific gravity of which is 1.27, what will be the height of its column in inches and in centimetres when the mercurial barometer stands at thirty inches?

3. What would be the height of the column in the preceding barometer tube if the glycerine were replaced by pure water? Express the result both in inches and in centimetres.

4. If the entire surface of the human body is 20 square feet, what is the total pressure upon it? Express the result in pounds weight and kilograms weight.

5. A room 15 feet long, 12 feet wide and 10 feet high, is filled with dry air at 0° C. at a pressure of one kilogram per sq. cm. What is the total weight of the air in the room in grams and in kilograms?

6. What is the total pressure of the air upon the floor of the above room in pounds and in kilograms?

7. If the closed arm of the U-tube (p. 138) were 16 in. above the zero line, how high would the mercury have to stand in the

longer tube to bring the mercury in the closed arm within 4 in. of the closed end?

8. If a certain mass of gas has a volume of 500 c.c. when the barometer stands at 75 cm., what will it be at 76 cm. pressure? What at 74 cm.?

9. Calculate the atmospheric pressure per sq. cm. when the barometer stands at 730 mm.

10. A tube 2 m. long, closed at one end, is filled with air and plunged, open end down, into a cistern of mercury, until the volume of the air is decreased one-half. How far is the lower end of the tube below the surface of the mercury in the cistern?

11. A litre of air at 0° C. and under a barometric pressure of 76 cm. weighs 1.293 grams. What will be the weight of 125 litres, at the same temperature, and under a pressure of 743 mm.?

PART III

SOUND

CHAPTER XI

NATURE OF WAVE MOTION

201. The Nature of Vibrations.—

Experiment 41.—Attach a string to a plumb-bob, or other suitable weight, and, holding the free end of the string in the hand, allow the weight to swing to and fro like a pendulum. Observe that the time required for the pendulum to complete a to-and-fro motion is practically the same whether it swings through a great or through a small distance.

Experiment 42.—Set the pendulum of the preceding experiment into vibration by moving its bob. Note the time that it continues swinging to and fro when released, before it comes to rest. Raise the bob higher than before, start the pendulum a second time, and observe that it will continue swinging for a longer time before coming to rest.

A tightly-stretched wire or string, such as a piano wire or a violin string, when momentarily moved out of its position of rest, will vibrate or move to and fro, like a pendulum. The sides of a bell, when struck, will also vibrate or move to and fro like a pendulum, or like the piano or violin string.

These to-and-fro motions, whether of the pendulum, of the wire, of the string, or of the sides of the bell, are called *vibrations*.

202. The Cause of the Vibrations of a Pendulum.—Vibrations or oscillations are never set up in a body without the expenditure of energy on the body. A body when vibrating, therefore, possesses more energy than it does when at rest.

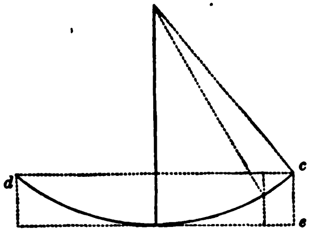

FIG. 92.

In order to set a pendulum in motion, work must be done on the pendulum against the force of gravity; *i. e.*, the bob of the pendulum must be raised, say to the position *c*, Fig. 92, through the vertical distance *c e*. If the pendulum bob weighs one pound, and the distance *c e* is one foot, then, disregarding the weight of the rod and friction, the amount of work done on the pendulum bob will be one foot-pound.

As the pendulum swings to and fro, it expends its energy, or does work, in overcoming the resistance of the air, and in friction against its point of support. If no additional energy be given to the pendulum, it will come to rest as soon as the amount of this work is equal to one foot-pound.

As the vibrating pendulum gradually expends its energy, the *amplitude* of its vibrations, *i. e.*, the distance through which the pendulum swings, becomes less; but the *period of the vibration*, or the time required to complete one to-and-fro motion from *d* to *c*, and from *c* back to *d*, remains the same for all amplitudes, provided these are small.

203. Elasticity Necessary to Vibrations.—Vibrations cannot be produced in inelastic substances, such as dough or putty. A rod of lead will not vibrate like the rod of steel shown in Fig. 93, because lead has but little elasticity.

In the case of the pendulum, the work done on the pendulum against the force of gravity permits energy to become stored as potential energy. In the case of a vibrating steel rod, the work done on the rod against the molecular forces developed through its elasticity permits the energy to become potential. In an inelastic bar these forces cannot be called into play, and vibrations are, therefore, impossible.

204. Energy Expended by Vibrating Bodies.—As a vibrating body moves to and fro, it expends its energy, or does work, in setting up a wave motion in the air or other medium which surrounds it.

Energy is always required to cause a body to vibrate, and the body will cease vibrating as soon as it has expended all the energy it has received.

205. All Energy of Vibrations Alternately Kinetic and Potential.—The energy possessed by any vibrating body is alternately kinetic and potential. The vibrating rod *a d*, Fig. 93, has all its energy potential when in the position *d b*, or *d c*, at the farthest points of its swings. On its return to *d a*, from either of these positions, all its energy is kinetic. When the rod is at *d b*, or *d c*, work has been done in producing flexure or bending, all the kinetic energy being converted into potential energy, represented by the elasticity of bending. The molecules of the rod are disturbed from their positions of equilibrium by being pulled farther apart on the convex side of the bar and crowded together on the concave side. The molecular forces thus brought into action through elasticity produce a push and a pull that carry the bar to the position *a d*, where, the molecules being in their normal positions, all the energy becomes kinetic. This energy of motion then carries the bar to *c d*, where all the energy is again potential.

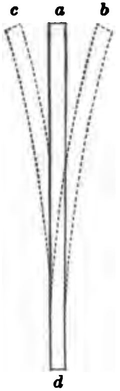

FIG. 93.

206. The Vibrations of a Cord Fixed at One End.—

Experiment 43.—Fasten a cord *A B*, at *A*, as shown in Fig. 94, and smartly shake it by the hand at *B*. Observe that a wave, as indicated by the curved line *B a E b D c d A*, will move along the cord from *B* to *A* and that, on reaching *A*, the wave will be reflected, and will move again toward the hand along the other curved line, and that these motions will give the particles of the string the appearance of moving alternately from *B* to *A* and from *A* to *B*.

In vibrations of this character the pulses and not the particles of the string move along the string from one point to another;

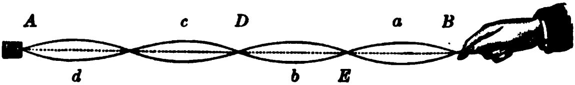

FIG. 94.

the particles of the string merely rise and fall, being sometimes above the straight dotted line, as at *B a E*, and sometimes below it, as at *E b D*.

207. No Continued Onward Motion of the Medium in Waves. —Wave motion is seen in the waves produced in a carpet that is being shaken, or in a field of grain, over which the wind is blowing. Here, although the waves move forward, there is evidently no continued onward motion either of the carpet or of the grain.

There is no onward motion of the water, when waves are started in deep water. Light bodies floating on the surface merely rise and fall with the waves, but do not continue to move onward with them.

In wave motion the particles move alternately backward and forward through comparatively small distances, while the waves, unless turned out of their course, move through considerable distances in one direction only.

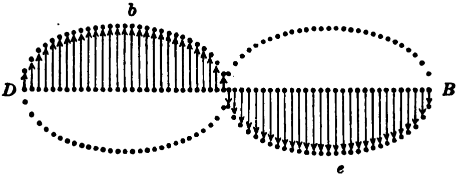

FIG. 95.

Thus, let the dots between *D* and *B*, Fig. 95, represent a row of particles in a string which, when at rest, will have the positions shown in the straight line *D B*. If a wave moves along the string from *D* to *B*, the particles do not move from *D* toward *B;* they simply move above or below the straight line *D B*, as shown by the arrows.

As in the case of the pendulum, the vibrations set up in cords, in rods, or in elastic media generally perform their to-and-fro motions in equal times, whatever the distance may be through which these motions take place; *i. e.*, whatever their amplitude. It is for this reason that a piano string continues to emit the same note throughout its vibrations, even when the string has almost come to rest.

208. Velocity of Waves.—The velocity of a wave is the distance through which the wave moves in a given time.

If the time be noted that a wave takes to move from one end to the other of a long wire or rope, it will be found that in the same wire or rope, whether the waves be long or short, the separate pulses move from one end to the other in the same time, but that in wires or ropes of different materials the waves travel with different velocities. The waves which produce sound *travel in the air with the same velocity*, whether they are the short waves which produce the shrill tones, or the long waves which produce the grave tones.

209. The Frequency or the Number of Vibrations per Second.—The number of complete vibrations, or to-and-fro motions, which a vibrating body makes in one second, is called the *frequency* of its vibration.

210. Transverse and Longitudinal Waves.—When the particles of the vibrating body move at right angles to the direction in which the wave is moving, the wave is *transverse*. When a stretched cord or wire is quickly moved from side to side so that a wave is produced, like that shown in Fig. 94, the wave is transverse.

If the particles move in the direction of the length of the body, or in the direction that the wave is moving, the wave is longitudinal. When a coiled spring is stretched at one end, a wave of compression and rarefaction travels along the spring, as shown in Fig. 96.

This is a longitudinal wave. Sound consists of longitudinal waves, usually in the air.

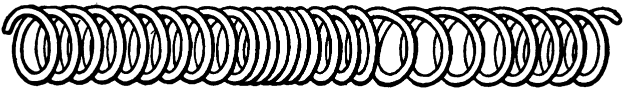

FIG. 96.

211. Vibrations of a Stretched Cord.—An elastic cord or wire, *a b*, Fig. 97, tightly stretched between the points *a* and *b*, if raised to the position *a c b*, and then released, will move to-and-fro on opposite sides of its position of rest *a e b*. Each complete motion from *c* to *d*, and back from *d* to *c*, is called a vibration. That is to say, as in the case of the pendulum, each complete vibration consists of a to-and-fro motion.

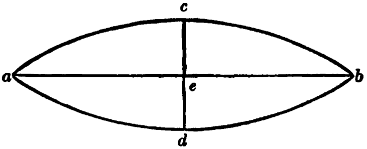

FIG. 97.

212. Laws for Transverse Vibrations of Strings.—The number of vibrations is—

1. Inversely proportional to the length of the string.
2. Inversely proportional to the diameter.
3. Directly proportional to the square root of the stretching force.
4. Inversely proportional to the square root of the density of the string:

That is, if we halve the length of a string, we double the number of its vibrations per second, and if we double the length, we halve the number of its vibrations. If we increase the stretching weight four times, we double the number of its vibrations per second. If we double the diameter of a string, we halve the number of its vibrations. If we use a string wrapped with wire, we decrease the number of its vibrations.

In a piano it is the short thin wires that vibrate rapidly and give the high shrill tones, while the long thick wires vibrate slowly and give the low grave tones.

These four laws are all expressed by this equation:

$$N = \frac{1}{2re}\sqrt{\frac{F}{\pi\, d}} \quad (29)$$

where n equals number of vibrations per second, r the radius, l the length, F the stretching force, and d the density.

CHAPTER XII

THE TRANSMISSION, REFLECTION, AND REFRACTION OF SOUND

213. The Cause of Sound.—

Experiment 44.—Sound a bell by striking it. Observe that when sounding loudly, a rapid shaking of its sides may be seen, and that when sounding less loudly, these movements may be detected by touching the sides lightly by the hand. Observe also that when these shakings cease, the sound ceases, as may be proved by pressing the hand against the sides, thus completely stopping the vibrations, when the sound at once ceases.

In the above experiment the bell sounds only while it continues vibrating. It can be shown that all bodies are vibrating while producing sound.

Sound is caused by the vibrations of a body.

A *tuning-fork* consists of a bar of steel, shaped as shown at *a b*, Fig. 98, and firmly supported on a hollow case *c*, of dry wood. When the fork is sounded by rubbing with a rosined bow, the arms *a b* move alternately toward and from each other, setting the air around them into vibration, and producing a musical sound.

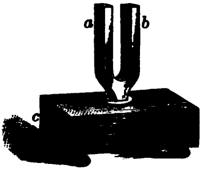

Fig. 98.

Experiment 45.—Partially fill a thin glass goblet with water, and rub the moistened fingers lightly against the edge, so as to produce a clear musical note. Observe that the surface of the water is ruffled with miniature waves produced by the vibration of the sides of the goblet. The waves may be produced more readily by drawing a rosined bow over the edge of the glass.

214. Double Meaning of the Word Sound.—The word sound has a double significance:

(1) The sensation produced when the effects of sound-waves reaching the ear are transmitted to the brain.

(2) The waves in the air or other medium which cause the sensation.

The assertion that there would be no sound if there were no ears is true, if by the word sound is meant the sensation; since, if there were no organs of hearing, there could be no transmission of the effect of the sound-waves to the brain, and, therefore, no sensation. If, however, the word sound be used to signify the thing causing the sensation, viz., the waves in the air, which probably is the sense in which the word is most frequently employed, then the assertion is untrue, since the existence of the sound-waves does not depend on the existence of an ear or brain.

A similar double significance is given to the words light, taste, and smell. The sun would shine, and a dish of strawberries would possess both fragrance and taste, whether there were an eye to see, a tongue to taste, or a nose with which to smell.

215. Manner in which the Vibrations are Conveyed from the Vibrating Body to the Ear.—As a vibrating body moves to and fro, it sets the air surrounding it into waves. These waves move out from the body in all directions, and, reaching the ear, produce the sensation of sound.

216. Nature of Sound-waves.—While the vibrating body, such as a bell, is sounding, its sides, in moving outward, crowd the particles of the air immediately in front of them into a smaller space, thus condensing the air. When its sides are moving in the opposite direction, the particles of air move with it, in order to fill the space left empty by the moving sides, thus effecting an expansion or rarefaction of the air. A complete vibration of the bell consists of a single motion of its walls inward and outward. A complete vibration of an air particle takes place during a condensation and the following rarefaction. The sound-waves surrounding the sonorous body are sensibly spherical.

The motion of the air particles in a sound-wave is alternately backward and forward *in the same direction* as that in which the wave is advancing; that is to say, sound-waves are made up of longitudinal vibrations. The greater the amount of energy in the vibrations of a sonorous body, the greater will be the number of particles of air crowded into the condensed place, and the smaller the number of particles of air left in the rarefied space, the louder will be the sound produced.

Some idea of the nature of sound-waves may be obtained from an inspection of Fig. 99, where the shaking of the bell is represented as causing waves or condensations and rarefactions in the air around it. In these waves the particles of air are alternately crowded together and separated from one another, as shown by the dark and light shadings, and move in straight lines, alternately directly from and toward the bell.

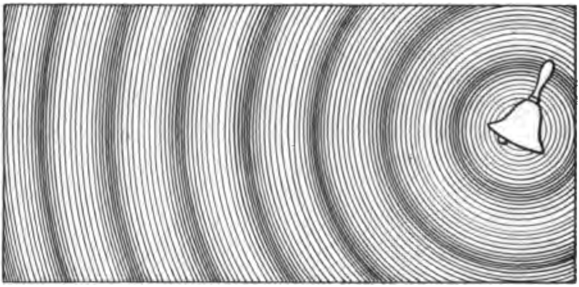

FIG. 99.

The nature of the motion of the particles of air may be roughly represented by the following experiment:

Experiment 46.—Place a number of glass marbles in a straight wooden trough, so that they touch one another. Cause a marble at one end of the trough to roll against the marble next to it. Observe that the marbles will not move on together, but that the first gives its motion to the second, and then stops; the second gives its motion to the third, and so on, through all to the end marble, which, having no marble to which to give its motion, moves on. A similar action takes place in the case of sound-waves: the vibrating body strikes the particles of air near it; these give their motion to the particles of air beyond them, and then stop; and these particles to others beyond them, and so on until at last the waves reach the ear, and we hear the sound.

The more rapid the vibrations of the sonorous body, *i. e.*, the greater the number of vibrations per second, the shriller will be the sound produced.

The greater the energy imparted to the sonorous body producing the sound, or the greater the amplitude of the sound-waves, the louder will be the sound produced.

The air particles do not continue to move onward from the vibrating body until they reach the listener's ear. They move a short distance, condensing the air before them, and then stop and move in the opposite direction. Meanwhile, the air condensed by the first pulse expands or moves outward and condenses the air in front of it, and then moves backward. This condensed air then expands and condenses the air in front of it, until finally the last condensed or rarefied pulse enters the listener's ear.

217. A Medium Necessary to Transmit Sound.—Since sound is transmitted by waves, some elastic medium to be set into waves must exist between the sounding body and the listener's ear, in order that the sound may be heard. If a bell be struck in a vacuum, no sound will be heard, since there is no material medium to be set into waves to carry the sound. In Fig. 100 a bell is suspended by a thread inside a glass globe *B*. If the air be removed from the globe by means of an air-pump, no sound will be heard when the bell is struck.

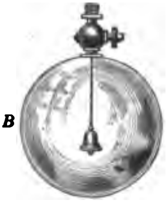

FIG. 100.

Sound-waves are transmitted through air because the air is elastic. As we have already seen, *any elastic substance will transmit sound.* Therefore, gases, liquids, and solids may all transmit sound.

Experiment 47.—Ring a bell under water. Observe that the sound may be heard by those standing near the water. Here the water must have transmitted the motions of the bell. The sound of the bell will be more distinctly heard if the hearer's ear is under the water.

218. Velocity of Sound in Air.—Time is required for sound to travel from one place to another. We can see a man at a distance strike a blow with a hammer before we hear the sound. During a thunder storm we see the lightning before we hear the thunder.

By measuring the distance through which sound-waves move in a given time, the velocity may be determined by dividing the distance by the time; or,

$$V = \frac{S}{t}. \quad (1)$$

As a result of many careful measurements, the velocity of sound in air, at the temperature of melting ice (32° F. or 0° C.), is 1090 feet (332.2 metres) per second.

The velocity of sound in all elastic media diminishes with the increased density of the media. Therefore, so far as density is concerned, sound would move less rapidly through liquids and solids than through gases. The velocity, however, increases with the elasticity of the media, and since the increase of elasticity in liquids and in solids is greater than the increase in density, the velocity of transmission is greater in liquids and in solids than in gases.

The velocity of sound in water is about four and one-half times greater than its velocity in air (1435 metres per second).

219. Effect of Temperature on the Velocity of Sound.—The velocity of sound in air increases with the temperature. This is due to the fact that an increase of temperature decreases the density, the pressure or elasticity remaining unchanged.

In air the velocity of sound increases about 1.1 feet per second for each degree of the Fahrenheit thermometric scale, or nearly 2 feet for each degree Centigrade.

When allowance is made for the difference in temperature, the velocity of sound is the same in the upper and less dense regions of the atmosphere as at the surface of the ground, because, although the density is less in the upper regions, the elasticity is also less to the same degree, and the ratio of elasticity to density, upon which the velocity depends, remains unchanged.

220. Velocity of All Ordinary Sounds the Same.—In the same medium all sound-waves travel with the same velocity, no matter whether the waves be long or short. All sounds, therefore, whether shrill or grave, must travel with the same velocity. Were this not the case, it would be impossible to obtain pleasing effects from the music of an orchestra when at any considerable distance from it.

Sound travels faster with the wind than against it, the sound-waves being carried bodily forward when travelling with the wind, and backward when travelling against it.

221. Acoustic Shadow.—When an intervening object, such as a house or high wall, prevents the free onward movement of sound-waves, an acoustic shadow is produced, the shape of which, like that of shadows cast by light, depends on the shape of the intervening object.

To a distant observer the roar of a train at once ceases when it enters a tunnel.

Acoustic shadows are less distinctly marked than are those cast by light, because the sound-waves are so much longer than the waves which produce light.

222. Reflection of Sound.—When nothing interferes with their progress, sound-waves move in all directions in straight lines. But when they meet a suitable obstacle, sound-waves, like elastic bodies, are reflected or thrown off at an angle equal to that at which they struck the obstacle. This change in the direction of sound-waves is known as *the reflection of sound.*

The smooth and hard surfaces of elastic bodies are the best reflectors of sound-waves. A smooth water surface forms an excellent reflector of sound. Cloths, curtains, and other draperies scarcely reflect the waves at all.

223. Echoes.—An echo is a sound heard by means of sound waves reflected by a distant body.

In order to produce an echo it is necessary:

(1) That there should be a fairly extended surface capable of reflecting sound-waves and thus throwing them back again to the hearer's ears.

(2) That the distance of this reflecting surface be such that the direct sound ceases before the reflected sound is heard.

In ordinary speech there are about five syllables uttered in each second. If, therefore, the reflecting surface is at such a distance from the speaker that it takes one-fifth of a second for the sound-waves to move from him to the reflecting surface and back again to his ear, then, after he has ceased speaking, and all sounds of his voice have died away, he will hear the last syllable he uttered. The first syllable uttered is reflected to him and reaches his ear just as he begins the second syllable, but he does not hear it as a distinct sound.

At the temperature of 60° F. (15.5° C.), the velocity of sound is about 1120 feet (341.3 metres) per second. During the one-fifth of a second, the waves would travel 224 feet. If, therefore, the speaker is standing in front of a reflecting surface which is 112 feet distant, and is speaking at the rate of five syllables per second, the last syllable will be heard after all the direct sound has ceased. If the reflecting surface is 224 feet distant, the last two syllables will thus be heard; if it is 560 feet, the last five syllables will be heard after the speaker ceases talking.

Very sharp, quick sounds produce a less permanent effect on the ear, and may, therefore, cause distinct echoes when the reflecting surface is less distant.

If the time required for the sound-waves to move toward or from the reflecting surface is less than one-fifth of a second, the reflected sound is not heard as a separate sound, but is blended with the direct sound.

If the reflecting surface is so near the speaker that the direct and reflected sounds reach the ear at nearly the same time, the original sound is prolonged and strengthened, otherwise the two sounds produce confusion.

In a properly proportioned hall, the voice of a speaker is strengthened by the waves reflected from the walls and ceiling, reaching the ear at nearly the same time as the direct sound. When, however, the hall is large, the reflected sound is apt to confuse the direct sound by the partial echoes produced. The confusing effects caused in this way in large empty halls are greatly diminished when the halls are crowded, since the bodies of people are bad reflectors. Curtains and drapery have a similar effect.

When the source of sound is between two opposite walls, or walls very nearly opposite, the waves are thrown alternately back and forth between the walls, thus repeating the original sound many times. These echoes are called *multiple echoes*.

224. Whispering Galleries.—If two curved mirrors, *A* and *B*, be placed facing each other, as shown in Fig. 101, and any sounding body, as a watch, be suspended at a certain distance in front of the mirror *A*, the waves after reflection from both mirrors will collect at a point *C* in front of the mirror *B*. From whatever part of the mirrors the waves have been reflected, they will all reach the point *C* at the same time. The ticking of the

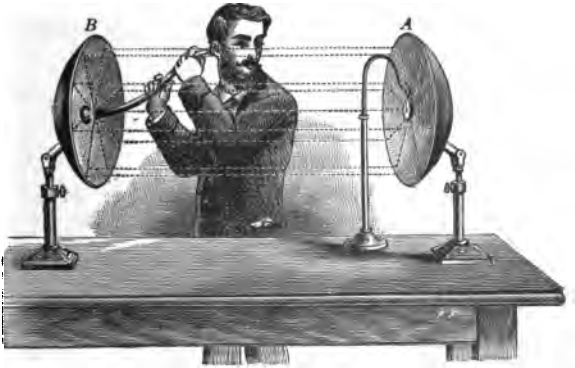

FIG. 101.

watch may, therefore, be distinctly heard by a person listening as shown in the figure.

Sometimes the ceilings and walls of a room are of such shape that a person standing in a certain position may distinctly hear all that is said by another person at a distance in some other part of the room, though speaking in but a faint whisper. The shape of the ceilings or walls is such that all the sound-waves reflected from different parts are brought by reflection to the place where the first person is standing. This frequently happens in rooms with dome-shaped ceilings. The name *whispering galleries* is given to such rooms.

In the dome of St. Paul's in London persons standing on opposite sides of a gallery, extending around the inside of the dome, may converse in faint whispers. The person talking places his mouth near the wall; the one listening holds his ear near that portion of the wall directly opposite.

225. The Effect of Distance on Sound.—If we are walking toward a distant bell while it is sounding, we notice that the sound grows louder as we approach the bell.

The speaking-tubes which connect the different rooms in a building enable a person talking in a moderate tone to be distinctly heard by a person listening in another part of the building. Here the intensity of the sound is not so greatly diminished, because the sound-waves, confined to the air in the tube, move in one direction only, and do not spread outward in all directions. For the same reason the faint sounds conveyed by the string or the wire in the string-telephone are distinctly heard at the other end.

Experiment 48.—Speak faintly into an empty water hose. Observe the fact that a person listening at the other end can hear distinctly what is said.

PROBLEMS

1. A piano string is vibrating with a frequency of 256 vibrations per second. What will be the frequency if the string be

shortened to $\frac{1}{2}$ and $\frac{1}{8}$ of its length respectively, the stretching weight remaining the same?

2. Suppose that a human voice has been heard in the open air a distance of 700 feet. Assuming the temperature of the air to be 60° F., what time will be required to transmit the sound of any syllable?

3. What time will be required to transmit the above sound if the temperature of the air is 32° F.?

4. A distant man is seen to strike a blow with a hammer. Four seconds elapse before the sound of the blow reaches the ear of the observer. What distance is the man from the observer if the temperature of the air is 70° F.?

5. A lightning flash is observed to strike a distant object six seconds before the thunder is heard. What is the distance of the object from the observer, the air being at the temperature of 60° F.?

CHAPTER XIII

THE CHARACTERISTICS OF MUSICAL SOUNDS.—MUSICAL INSTRUMENTS

226. Musical Sound and Noise.—The vibrations of sounding bodies produce a variety of sounds. These, generally speaking, may be divided into musical sounds and noises. All sounds, whether musical or noisy, consist of various combinations of simple, musical sounds.

Musical sounds are characterized by smoothness and regularity. When this smoothness and regularity are absent, noises are produced.

The unpleasant effect produced on the ear by noises may be compared to a similar effect produced on the eye by a flickering light. In both cases the unpleasant feeling is probably caused by the sudden and abrupt changes transmitted by these organs to the brain.

227. Musical Sounds Produced by Regular Impulses.—That successive impulses will produce musical sounds, when they follow each other with sufficient rapidity, is a matter of common experience. As the teeth in a circular saw successively strike the board it is sawing, a musical sound is produced.

228. The Characteristics of Musical Sounds.—Although musical sounds may differ in a great variety of ways, yet these differences may all be traced to three peculiarities or characteristics; viz., the *intensity or loudness*, *the tone or pitch*, and *the quality or timbre*.

229. Intensity.—By the *intensity* of a sound is meant that peculiarity which enables us to distinguish between a *loud* and a *feeble* sound.

When a bell is struck vigorously, it emits a loud sound, because the distance through which its sides swing is comparatively great, and the air around the bell is considerably condensed and rarefied.

Experiment 49.—Stretch a wire firmly between two stout hooks securely fastened to the top of a table. Pluck the wire gently with the fingers: a musical sound will be heard. Now pluck the wire at the same point, but with more force, and observe that a note will be heard louder than before, but neither higher nor lower in pitch. The two notes are of the same pitch, but they differ in their intensity or loudness.

The speaking trumpet is a device employed to cause the voice to be heard at great distances. It is conical in form, and trumpet-shaped at its larger end. The small end is held to the mouth of the person talking.

Experiment 50.—Roll a piece of stout pasteboard into a cone, being sure that it is closed tightly at the sides; place the mouth at the small end, and talk or sing into the cone. Observe that the sound of the voice will be greatly strengthened. Point the cone directly at a person standing at the far end of a room, and whisper; he will be able to hear distinctly all that is said, while those on either side of the instrument, though nearer it, are unable to [illegible] megaphone is a familiar example of this principle.

The ear-trumpet is an instrument employed to aid deaf persons in hearing. It acts by concentrating the sound of the voice on the listener's ear. The shape of the ear-trumpet is similar to that of the speaking-trumpet, but the small end is placed in the ear and the person talks into the large end.

Experiment 51.—Place the small end of the paper cone used in the preceding experiment in a person's ear and whisper into the large end; observe that he will hear much more distinctly than without the cone. Go to the far end of the room and again whisper, though somewhat louder, and he will still hear what is said.

230. Pitch.—By the pitch of a musical sound is meant that peculiarity which enables us to distinguish between sounds that are *high* or *low*, *shrill* or *grave*.

Pitch depends on the number of vibrations per second imparted by the sounding body to the air; or, in other words, on the *frequency*. The greater the number of vibrations, the higher will be the pitch of the sound, or the shriller the note. Thus, when a circular saw is in motion, the more rapid its rotation, the shriller will be the sound which it produces.

A wheel furnished with teeth on its circumference, and supported on a suitable frame, as shown in Fig. 102, may be set in rapid rotation by means of a cord wrapped around its axis. If, now, a card be held against the teeth, a musical sound will be produced, the pitch of which will be shriller the more rapid the rotation. As the wheel gradually moves slower and slower, the pitch of the note descends in a marked manner.

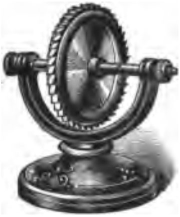
FIG. 102.—Savart's wheel.

The less the length of a vibrating string or wire, the more rapid its vibration; hence the shriller the notes it emits. The shrill, treble notes of a piano are produced by the short, thin strings; the grave, bass notes, by the long, thick strings.

After a piano-string has been struck, the sound will gradually become fainter, because the string moves through a shorter and shorter distance. The pitch of the note, however, will not change, since the frequency of the vibration remains the same.

Experiment 52.—Cut out a bridge or rectangular-shaped piece of hard wood, with a flat base and a sharp edge, rather too high to go under the wire stretched across the top of the table, as described in experiment No. 49, Lift the wire and place the bridge under it so that the wire will press firmly against its sharp edge. Observe that on sliding the bridge from one end of the wire to the other, the shorter the portion of the wire vibrated, the shriller will be the note produced, that is, the higher will be its pitch.

Experiment 53.—Move a moderately long blackboard-crayon, held loosely in the fingers, over the surface of a blackboard, so as to produce a shrill sound. This sound is caused by a series of taps rapidly following one another. Examine the line made by its motion over the board, and observe that it consists of a number of separate marks made each time the chalk taps against the board. Alter the pressure of the chalk on the board, so as to obtain sounds of different pitch. Examine the lines and observe that the shriller sounds were produced by the greater number of taps in a given time.

231. The Limits of the Human Ear.—The limits of hearing vary in different persons. No one, however, can hear sounds produced by less than 16 complete vibrations per second, or by more than about 40,000 per second. If the vibrations are less than 16 per second, we hear each separate tap or blow; if they are more than about 40,000, the sound becomes too shrill to be audible.

232. Doppler's Principle.—Since the pitch of a note depends upon the number of vibrations which reach the ear per second, if the sounding body is moving toward or from the ear at a sufficiently rapid rate, the number of vibrations received per second by the ear will vary enough for it to detect a difference in the pitch of the note. This fact was discovered by Doppler. That this is a fact may easily be proved by noticing the change in the pitch of a locomotive whistle as the engine passes the observer. As the engine approaches the pitch is higher than if it were at rest; as it recedes it is lower; on passing, the change is very noticeable. The same effect is perhaps more frequently noticeable as a rapidly moving bicycle passes an observer, the bell ringing at the same time. As it approaches, the pitch is higher than the note given out when standing still, and as it recedes, it is lower, so that a very noticeable "swoop" takes place as it passes.

233. Methods of Determining Pitch.—The pitch of a musical tone may be determined:

(1) By the siren.
(2) By Savart's toothed wheel.
(3) By some graphic method.

234. The Siren.—A simple form of apparatus which may be used to determine the pitch of a tone consists of a disk of sheet metal (Fig. 103), with circular holes at equal distances, arranged in concentric circles. This is rotated by means of pulleys, and a jet of air blown through the holes by means of a bellows. As the velocity of revolution increases, the pitch of the tone rises.

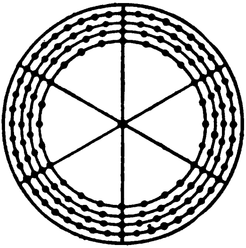
FIG. 103.

235. Savart's toothed wheel (Fig. 102), when used to determine the pitch of a musical note, is provided with a counting device. The number of vibrations required to produce the note is determined by multiplying the number of revolutions of the wheel by the number of teeth.

236. Graphic Method.—If a stylus or point be attached to one of the prongs of a tuning-fork, *F*, and the fork, while sounding, be moved over the lampblack-coated surface of a glass plate *A*, Fig. 104, a sinuous or wavy line will be produced as shown. Since each wave is produced by one complete to-and-fro motion of the fork, it is evident:

(1) That if the time required to draw the fork over a given length of the plate is known, the number of vibrations performed in that time may be directly determined by counting the number of elevations and depressions in the sinuous line.

Such an apparatus is called a *phonautograph.*

(2) That if the number of vibrations produced by the fork in a second is known, the time required to draw it over the plate, through a distance equal to an elevation and depression, may be determined. Thus, if the fork makes 1024 vibrations per

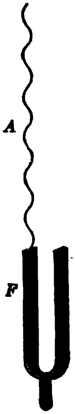

FIG. 104.

second, a very small fraction of a second may be measured, since the fork makes one complete vibration in $\frac{1}{1024}$ of a second, and if the motion be sufficiently rapid, the distance may be readily divided into hundredths or thousandths.

Such an apparatus is called a *chronograph.*

237. The Musical Scale.—The disk mentioned in Par. 234 if properly made, may be used to explain what is meant by the musical scale. It should have four concentric rows of holes, the number of holes in each row being respectively 48, 36, 30, and 24. If the disc is rotated at a constant speed and the air jet directed against each row of holes in succession, a series of notes will be produced in the relation, do, mi, sol, do′. If the speed of the rotation is increased, the pitch of all the notes will rise, but the relations between them will remain unchanged. This shows that the series of notes, do, mi, sol, do′, is produced by notes whose vibrations bear to each other the relations 4, 5, 6, 8, and that this relation holds true no matter what the vibration numbers are.

The two notes, do and do′, which were given by the rows having 24 and 48 holes, have properties in common which enable us to know that they are more like each other than any other notes. When they are sounded together, they produce harmony. Such notes are said to be an *octave* apart and the ratio of their vibration numbers is the simplest possible, that is, 24: 48:: 1: 2. In the same way we notice that the combination of do and sol is harmonious and their ratio is 2: 3. When sol is sounded with do′ the harmony is also pleasing and the ratio is 3: 4. Therefore, it is evident that what we call harmonious intervals are all produced by notes whose vibration numbers have a very simple ratio to each other.

The use of the musical scale long preceded a knowledge of the relation of notes which produced the pleasing effect. Sounding do, mi, and sol together produces a pleasing combination of tones called the major chord. The major diatonic scale is built up of major chords. The final result is a series of eight notes whose vibration numbers bear a definite relation to each other. This is shown by the following arrangement:

Name of note........	DO	RE	MI	FA	SOL	LA	SI	DO′
Letter..............	C	D	E	F	G	A	B	C
Vibration number.....	24	27	30	32	36	40	45	48
Ratios to Do........	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

The intervals between notes which produce harmony when sounded together may also be studied by means of the sonometer. This consists of a box, on top of which are wires stretched by weights or springs, and whose length is adjustable by means of movable bridges.

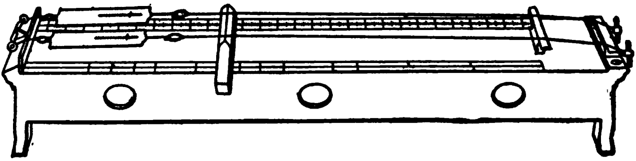

FIG. 105.

By applying the laws given in Par. 212 the different notes may be obtained. This may most easily be done by keeping the wires alike and at the same tension, but varying the length by means of the movable bridge. When the string vibrates as a whole it gives its fundamental note. If a second string of half the length is vibrated at the same time, the note is the octave of the first. If the length of the second wire is made $\frac{2}{3}$ of the first, the note has a vibration number of $\frac{3}{2}$ and the combination of do and sol thus obtained is pleasing. We again find that if the intervals are harmonious, the vibration numbers bear a simple ratio to each other.

Any number whatever may be taken as the vibration number of C and a scale built up on this. Even if we limit ourselves to a note of a definite name, as middle C, we find that it is assigned different numbers under different conditions. In scientific physical work it is given 256. In what is called concert pitch it is 274.

238. Quality or Timbre.—When the same note is sounded with equal loudness on two different musical instruments, as on a piano and on a flute, although the notes are of exactly the same pitch and intensity, yet there is something which enables the ear to distinguish one note from the other. Or, when two persons are speaking in the same tone, we can recognize a difference in the sounds produced; these peculiarities are known as the *quality of the sounds.*

239. Fundamental Tone of a String.—When the tightly stretched wire or string *a b*, Fig. 103, is caused to vibrate transversely as a whole, it produces the lowest or gravest tone it is capable of producing. This tone is called its *fundamental tone.*

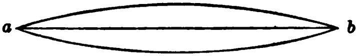

FIG. 106.

240. Overtones or Harmonics of a String.—It is difficult to make the string shown in Fig. 106 vibrate only as a whole. There is a tendency for the string at the same time to divide itself into a number of shorter parts, which produce additional tones called *overtones.* These overtones are shriller than the fundamental tone, as the lengths of the parts into which the string is divided are smaller than the entire length.

In the notes of all musical instruments overtones accompany the fundamental tone, and impart to the tone its peculiar quality or timbre. The different overtones are of unequal intensity or loudness in different instruments.

In some instruments the overtones produce pleasing chords with the fundamental tone. In such cases the instruments produce brilliant pleasing tones. In other instruments, however, the overtones produce discords with the fundamental. In these cases the tones produced are flat, harsh, and unpleasant.

Some pianos produce more brilliant tones than others because the strings are so struck as either to prevent altogether the formation of objectionable overtones or greatly to decrease their intensity.

241. Sympathetic Vibrations.—

Experiment 54.—Suspend a weight of 10 or 15 lbs. by a string, and let it swing as a pendulum. Note the time of its oscillation. Now, while it is swinging very gently, blow a puff of air against it from the mouth, just as it is *moving away*. Wait until it is again moving away, and give it another puff of air. Do this thirty or forty times and observe the fact that the pendulum will acquire a considerable increase of motion.

While the pendulum is swinging freely, give it the puffs of air *when it is just beginning to move toward you*, and the motion will be stopped sooner than otherwise.

Experiment 55.—Partially raise the lid of a piano, and place the foot on the loud pedal; lean over the instrument, and sing any note into it, in a loud voice. On ceasing to sing, observe that the same note is given back by the piano. Now sing a different note, and observe that the piano will give back this particular note; and so with any other note sung into it. The sound-waves produced by the voice have struck against all the strings of the piano, but have only set in vibration those particular strings that are capable of giving sounds of the same pitch as their own. Vibrations so produced are called *sympathetic vibrations*.

The cause of sympathetic vibrations is as follows: the sound-waves strike all the strings, and give each a very feeble push. If the time of vibration of any string be exactly the same as the time of the vibration of the sound wave striking it, the next forward impulse which the waves give to the string will be received just as it is beginning to move forward, and hence the motion acquired by the first impulse is increased by the second impulse, and as the same is true of all the other impulses, the string eventually acquires considerable motion, and emits an audible sound. If, however, a string has a rate of motion different from that of the sound-waves, it will sometimes receive a forward impulse from the waves when it is moving in the opposite direction, and its motion being thereby diminished, it can never acquire any considerable motion,

242. Examples of Sympathetic Vibrations.—If various powerful notes be sung, or otherwise produced, near a table on which a number of goblets and glasses of different sizes are placed upright, when the proper note is struck, one of the goblets or glasses will be set into sympathetic vibrations and will emit this note.

Experiment 56.—Place two tuning forks whose times of vibration are equal, that is, which have the same pitch, so that the open ends of their boxes face each other. Set one in vibration and, permitting it to continue sounding for a while, stop its vibration by touching it. The second tuning-fork will give out its note, thus showing that it is vibrating. The vibrations of the air caused by the motion of the first fork, being of the exact period of the second fork, have set it into vibration just as the singing of the note into the piano did in Experiment 57. If the vibrations of the fork are not audible, they may be shown by suspending a light object, as a microscopic cover-glass, so that it rests lightly against one prong. It will be seen to vibrate when the other fork is made to vibrate.

243. Resonance.—We have already seen how the voice of a speaker may be strengthened by the reflection of sound-waves from the ceiling and walls of a room.

A mass of air whose dimensions are such as to enable it, when set in motion by any sound, to vibrate in exactly the same time as that sound, will greatly increase its intensity by what is called *resonance*. Resonance of this kind is, therefore, dependent for its action on sympathetic vibrations.

The strings of a violin or guitar have too small a surface to set much air in motion. The notes produced by these instruments are greatly aided by the vibrations of the wood forming the body of the instruments. It is on the elasticity of the wood, and its ability to accept different rates of motion from the strings, that the musical value of the instrument depends. This appears to increase with the age of the wood and the number of times the instrument has been used.

Experiment 57.—Stretch a wire across the corner of a room to the walls, pluck it, and observe the note it gives. Now stretch it when attached to hooks in the top of a table and observe that it gives a much more powerful sound, because the table now takes up the motion of the wire much better than do the walls of the room.

In order to increase the effect of the overtones of a note sufficiently to enable them to be distinctly heard, instruments called *resonators* are employed. Resonators consist of hollow spheres of brass, as shown in Fig. 107, with openings at *a* and *b;* one of these, *a*, is placed in the ear, and at the other the sound-waves enter. If there is present in any tone an overtone whose rate of vibration is exactly the same as the rate in which the air contained in the sphere can vibrate, the resonance of the sphere will cause this overtone to be distinctly heard.

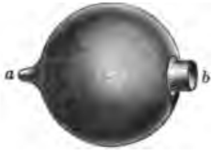

FIG. 107.

The resonant case on which a tuning-fork is mounted should contain a column of air whose rate of vibration is exactly that of the fork.

Across the far end of the tube or alley-way leading from the outside of the ear inward is a tightly stretched drum-head, or closed gate, called the *tympanum.* The column of air contained within this tube is capable of resounding to and greatly strengthening certain sounds by resonance.

Experiment 58.—Tie two strings to a poker, or to a bar of steel or iron, some little distance from the ends. Hold the ends of the string over the end of one of the fingers of each hand, letting the poker hang in a horizontal position. Now insert in the ears the fingers holding the strings, being careful that the strings do not rest against the body. Let some one strike the poker near the middle, and observe that *a sound will be heard like that of a large bell when you are very near it.* Here the vibrations of the poker are transmitted through the strings to the columns of air within the ears, which by resonance strengthen the sound. The effect is also due to the vibrations being carried through the bones of the head directly to the ear.

The air which fills any hollow body will resound to some particular note. When a shell is held close to the ear, a sound is heard, which a pretty superstition of childhood regards as the imprisoned sounds of ocean waves beating against a shore. The sounds are caused by the air within the shell strengthening, by its resonance, the feeble sounds that are always present in the air. Similar sounds may be heard by holding an empty pickle-jar or tomato-can near the ear.

244. Resonance Tube.—The principle of a resonance may be conveniently used to determine the pitch of a tuning-fork. Place a tube about a couple of feet long and an inch or so in diameter in a cylinder of water, as illustrated (Fig. 108). Set a tuning-fork into vibration and hold it over the open mouth of the tube. Vary the length of the air column by raising or lowering the tube in the water until the resonance is greatest and the note is best reinforced. Measure the length of the air column and the diameter of the tube. Then, since the air pulse must go to the end of the tube and back while the fork is making a half vibration, the wave length is four times the length of the air column. That is, $L = 4\,l$, where L = wave length and l = length of air column. It is found by experiment that the diameter of the tube affects the result, so that this must enter as a correction. Rayleigh found that one-half the diameter of the tube should be added as the correction. Then,

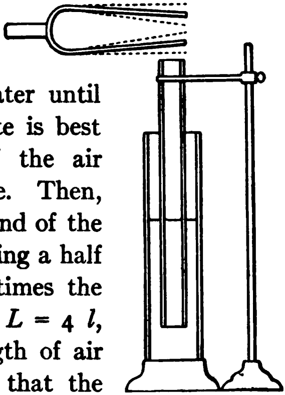

FIG. 108.—Resonance tube.

$$L = 4\,(l + r).$$

But the velocity of sound is proportional to the product of the number of vibrations and the wave length, that is,

$$V = N\,L. \quad (30)$$

Therefore,

$$V = 4\,N\,(l + r). \quad (31)$$

This experiment, therefore, gives a method of finding the velocity of sound in air when the number of vibrations of the fork is known, or it may be used to determine the pitch of the note by using the correct value for the velocity of sound in air at the temperature at which the experiment was made.

245. The Interference of Sound Waves.—When two notes of the same intensity and pitch are simultaneously sounded, they sometimes strengthen, *and sometimes partly or completely obliterate, each other.*

When two separate notes are sounded together, if the waves of one of the notes condense the air at the same time that the waves of the other note are condensing it, the air will be more condensed. The amplitude of the resulting wave will be greater and the sound will, therefore, be louder.

If, however, the waves of the one note condense the air at the same time that the waves of the other note are rarefying it, and the amplitude of each set of waves is equal, the air will be neither condensed nor rarefied and silence will result. If the amplitudes of the two sets of waves are not equal, a sound will be heard less intense than either of the two sounds. These effects are known as the *interference* of sound.

246. Beating.—When two notes of nearly but not exactly the same pitch are simultaneously sounded, a peculiar throbbing or palpitating sound, alternating in strength and feebleness is heard. This effect is known as *beating* and is due to the interference of two sounds. At certain times both sounds are condensing or rarefying the air simultaneously, while at other times one sound is condensing the air while the other is rarefying it. Hence, the alternations in strength and feebleness.

When the beats follow one another too rapidly, they cease to be heard distinctly, and merely cause an appreciable roughness in the two sounds. When a certain rapidity is reached, the beats cease to be heard.

Two notes of nearly the same pitch, when sounded separately, are with difficulty distinguished, but when sounded together, the difference in their pitch is at once recognized from the resultant beating. This principle is utilized in tuning an instrument. The note is judged to be in unison with a standard tuning-fork or pitch-pipe, when the two can be simultaneously sounded without beats being heard.

247. Musical Instruments.—Musical instruments may be divided into three classes:

(1) *Stringed instruments.*

(2) *Wind instruments.*

(3) Instruments in which the sounds are produced by the *vibration of plates or membranes.*

248. Stringed instruments are those in which sounds produced by the vibrations of strings are suitably intensified by resonance. Examples of stringed instruments are seen in the piano, the harp, the violin, the violoncello, the guitar, and the banjo. In the piano and the harp there is a separate string for each note. In each of the other instruments the same string is made to give different notes by pressing it at different points with the finger, and thus practically shortening it. The tighter any string is stretched, the less the length of the string, and the smaller its diameter, the shriller the note which it will give.

249. Wind instruments are those in which sounds are caused by the vibrations of a column of air contained within the instrument. The pitch of the notes depends upon the dimensions of the air-column, and upon whether the tube containing the column of air is open at both ends or at but one end.

The column of air in a wind instrument may be set into vibration in a number of ways, of which the most important are:

(1) By means of a *mouth-piece.*

(2) By means of a vibrating plate called a *reed.*

In the organ-pipe the vibrations of the air-column are produced by the action of a mouth-piece. The organ-pipe is placed on a box called the wind-chest, supplied with air from a bellows. The air entering through the opening *a*, Fig. 109, passes through a narrow slit *c*, and escapes at the opening *o*. Here the air impinges on the sharp edge as shown, and a part of it is projected into the pipe, producing a pulse of compression which travels down the tube and is reflected at the end. The reflected wave meets the next pulse and so the air column is set into vibration. The note produced, therefore, depends upon the length of the air column set into vibration. In an open pipe the length of the wave is twice that of the pipe. In a closed pipe the length of the wave is four times that of the pipe.

A reed is a thin, vibrating plate of any elastic material, which is moved backward and forward by the air. The notes of reed-organs, accordions, and jews-harps are caused by the vibrations of reeds.

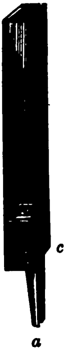

FIG. 109.

Experiment 59.—Cut a stout wheat straw into a length of about four inches from the knot. With a sharp pen-knife cut a slit *a* down the side of the knot *b*, as shown in Fig. 110. Now place the mouth completely over the cut part and blow, and observe the musical note that will be produced. The pitch of this note will increase if the length of the straw tube is lessened by cutting a piece off the open end.

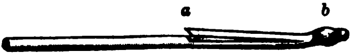

FIG. 110.

Experiment 60.—Prepare a straw reed as before, but use a larger straw, and cut holes in the side about one inch apart. Sound the reed when the holes are all open, and remember the pitch of the note. Now, with one finger close the hole nearest the knot end, and observe that the pitch of the note produced will be lower; close the next hole; still keeping the finger on the opening previously closed, the note will be still lower. These effects are the same as would be produced by lengthening the pipe.

In the flute, the flageolet, and the fife the different notes are produced by virtually altering the length of the air-column by opening or closing holes in the side of the instrument.

250. Vibrating Plates and Membranes.—In the music box the notes are produced by the vibrations of a series of steel teeth of different lengths, which are set into motion by pins projecting above the surface of a revolving cylinder.

In the xylophone, the notes are produced by the vibrations of plates of wood of different lengths. The notes of the cymbal are produced by the vibrations of brass plates; those of the drum, by the vibrations of a membrane.

251. The Phonograph, an invention of Edison, is a device for recording sounds and reproducing them at any future time. The principle of its operation consists essentially in causing a cutting point, attached to the centre of a flexible diaphragm, moving up and down under the influence of a speaker's voice, to leave on the surface of a rotating cylinder of hardened wax a permanent record of the movements of the diaphragm, and of using such indentations to reproduce in the same diaphragm the motions that caused them.

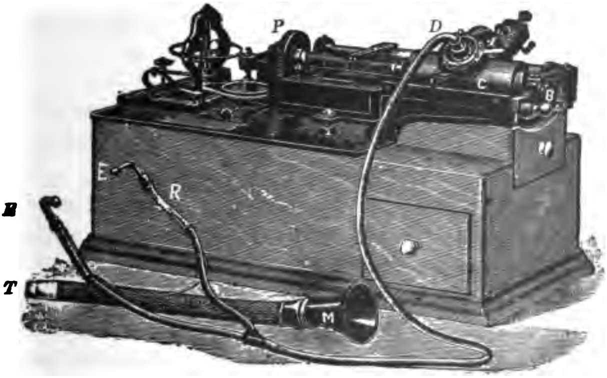

FIG. 111.

The construction of the phonograph is shown in Fig. 111. A metal cylinder is rotated on the axis, *A B*, by means of an electric motor placed inside the box support at *R*, through a belt passing over a pulley *P*. A flexible diaphragm *D* clamped at its edges, and provided with a cutting point attached at its centre, is so supported that on the rotation of *A B* it moves lengthwise on the axis *A B*.

In order to record the sounds of the voice, a hollow cylinder of hardened wax *C*, is slipped over the horizontal axis *A B*, and the cutting point on the diaphragm brought in contact with it, near one end. On the rotation of the cylinder a continuous spiral is cut on the surface of the cylinder. If, now, during its operation, the mouth-piece *M* attached to a flexible rubber tube *T* is fixed to the end of the diaphragm *D*, removing the rubber tube shown in the figure for this purpose, a person talking into *M* will cause the diaphragm *D* to cut indentations in the wax surface, the number of which will depend on the frequency of the sound-waves produced by the speaker's voice.

To cause the phonograph to reproduce the speech, the same diaphragm is employed, but the sharp cutting point is replaced by a blunt point. The wax cylinder is placed under the point, at the beginning of the record, and revolved by the motor. As the blunt point attached to the diaphragm follows the minute elevations and depressions cut in the surface of the wax, movements are imparted to the diaphragm exactly similar to those produced by the voice of the speaker. Consequently a person listening at the diaphragm can distinctly hear all that was originally spoken against it. In the figure, a flexible rubber tube, provided with ear-pieces, *E*, *E*, is shown attached to the diaphragm at *D*.

PROBLEMS

1. When the temperature is 20° C., a tube 15 in. long gives the best resonance for a tuning-fork. What is the vibration number of the fork?

2. What is the length of a closed tube which at 0° C. will give the greatest reinforcement to the sound of a tuning-fork making 256 vibrations per second?

3. What is the length of an open pipe that at 60° F. gives the note having 262 vibrations per second?

4. What is the length of a closed pipe that at 70° F. produces the note G, 392 vibrations?

PART IV

LIGHT

CHAPTER XIV

LIGHT—ITS NATURE AND CAUSES

252. The Nature of Light.—Light is a wave motion in an extremely tenuous medium called the *ether*. The bell rung in the empty vessel, shown in Fig. 100, cannot be heard because in the vessel there is no air to be set into waves. The carbon thread of an incandescent electric lamp, though placed in a glass vessel from which nearly all the air has been removed, readily sends its light across the space within the vessel. The light of the sun and stars reaches the earth across the apparently empty space which exists between these bodies and the earth. The ether fills all space, even that between the adjacent molecules and atoms of matter.

253. Light and Sound Waves.—Light, like sound, is a wave motion. Sound waves, however, take place usually in the air, while light waves take place in the ether. Moreover, the vibrations of sound are longitudinal; that is, the particles of air move to-and-fro in the same direction as that in which the sound waves are advancing, while the vibrations of light are transverse, that is, the ether is disturbed at right angles to the direction in which light-waves are advancing. The disturbances are probably not movements of the ether itself, but alterations in the electrical and magnetic condition of the ether.

254. The Undulatory Theory of Light assumes that light is waves or vibrations in the ether. By means of these waves the energy is transferred from one place to another. The transfer of energy by means of ether waves is called *radiation.*

Ether waves have been measured whose frequency is as high as about three quadrillions (3,000,000,000,000,000) of double or complete vibrations per second. Besides these there are waves whose frequencies are much lower. Those having a frequency between 392 trillions and 757 trillions possess the power of affecting the eye and producing the sensation of light. Since the frequencies of the ether waves are so great, their wave lengths must be extremely small.

Ether waves of any frequency, striking ordinary matter, may produce in it the phenomena of heat; or, when falling on a sensitized photographic plate, or on the leaf of a growing plant, may produce therein a chemical decomposition. This latter effect is called an *actinic effect.*

In either of these cases the waves of light, falling on matter, produce therein a to-and-fro motion of its molecules. When luminous effects are produced, these to-and-fro motions are of a frequency sufficiently great to affect the eye. In the case of the photographic plate, or of the leaf, the to-and-fro motions are sufficiently great to produce a decomposition of the molecules; in the case of heat, they warm the body.

There are, therefore, three classes of effects which ether waves may produce on ordinary matter; namely, heating effects, luminous effects, and actinic effects.

255. Double Meaning of the Word Light.—The word light, like the word sound, is used in two distinct senses:

(1) As the cause which produces the sensation; viz., the ether waves of the necessary frequency.

(2) As the sensation produced in the mind through the intervention of the eye.

In physics the first meaning is employed.

256. Sources of Light.—The principal sources of light are the sun and the fixed stars, chemical combinations, and electric currents. Nearly all the earth's light comes from the sun. Artificial light is obtained from a variety of sources, the principal of which are combustion and electric currents.

257. Luminous and Illumined Bodies.—A body which produces the light it gives off is called a *luminous body*. A lighted candle is a luminous body, since it produces the light which it emits. A body which shines by throwing off light it has received from a luminous body is said to be *illumined*. The sun is a luminous, and the moon an illumined, body. Nearly all visible bodies are illumined: we see them by means of the light they receive from luminous bodies.

258. Transparent, Translucent, and Opaque Bodies.—A *transparent* body allows light to pass through it in such a manner that we can see clearly through it the outlines of other bodies; water is transparent.

A *translucent* body allows light to pass through it in such a manner that we cannot see through it the outlines of other bodies; oiled paper is translucent.

An *opaque* body does not allow any light to pass through it; iron and wood are opaque.

Many substances that are opaque when in fairly large masses are partially transparent when in thin films; thus, a film of gold is transparent to yellowish-green light; a film of silver is transparent to a bluish light.

The difference between a transparent and a translucent body does not consist in the amount of light which passes, but in the manner in which the light passes.

A transparent substance permits luminous or illumined bodies to be clearly seen through it, because it does not change the direction of the rays of light which such bodies emit. A translucent body will not permit such bodies to be seen through it because it changes the direction of the light which passes through it. As the light comes out of the translucent body, it is scattered or diffused in all directions, so that only the surface of the translucent body is seen.

259. Ray, Beam, and Pencil.—A *ray* is a single line or path of light, taken in the direction in which the light is moving; a *beam* is a number of parallel rays; a *pencil* is a number of converging or diverging rays. A pencil of light is *converging* when the rays are all moving *toward the same point;* and *diverging,* when they are all moving *from the same point.*

260. How Bodies Become Visible.—Only those bodies are visible which throw off light in all directions. Both luminous and illumined bodies are, therefore, visible. A body which regularly reflects light cannot be seen. A clean plane mirror, placed in a doorway, cannot be seen, and may be mistaken for an open doorway. Ordinary mirrors are visible by reason of the light diffused from their tarnished or dusty surfaces.

A ray of light is invisible. We cannot see the rays which pass from the stars to the earth. The path of a ray through a dusty room is visible because the particles of dust in the air scatter or diffuse the light.

261. Direction in which Light Moves.—Light, like sound, moves in *straight lines,* provided the medium through which it is passing remains the same kind, and does not change in density.

That light moves in straight lines is evident from the following considerations:

(1) When a beam of light comes into a darkened room, it lights up the dust-particles floating in the air; we can then see that it moves in straight lines.

(2) The shape of a shadow depends on the shape of the body which casts it; this could only happen by the light moving in straight lines.

(3) If an opaque body be held between the eye and any visible object so as partly to hide it, the parts remaining invisible will be separated from

the visible parts by a line of the same general shape as the edge of the interposed body; the rays of light have evidently passed over the edge of the interposed body in straight lines and have not been sensibly bent around it.

(4) We point a gun directly at a mark, allowance being made for the wind and drop of the ball, because we assume the rays of light pass directly from the mark to our eyes in straight lines.

262. Intensity of Illumination.—Law of Inverse Squares.—Let *S*, Fig. 112, be a luminous point, and *A*, *B*, *C*, and *D*, square screens, one inch, two inches, three inches, and four inches in length of side, respectively. Then, it is evident that *A*, one square inch in area, will receive the same quantity of light as *B*, which has four square inches in area, *C*, which has nine square inches, or *D*, which has sixteen square inches. Consequently, the amount of light which falls on each square inch of surface is one-sixteenth at *D*, one-ninth at *C*, and one-fourth at *B*, of that which falls on *A*. That is to say, the intensity of illumination of the surface *A* is four times that of *B*, nine times that of *C*, and sixteen times that of *D*. But if *A* is one foot from *S*, *B* is two feet, *C* three feet, and *D* four feet. *Consequently, the intensity of illumination of a surface from a point source of light varies inversely as the square of the distance between them.*

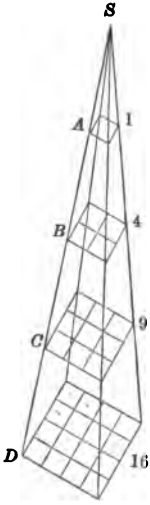

FIG. 112.

If the light emitted by *S* is doubled, that falling on all the plates will be doubled. If the light emitted by *S* is halved, that falling on all the plates will be halved. *Consequently, the intensity of illumination of a surface varies directly with the luminous intensity of the source.*

263. Photometers.—The luminous intensity of different sources of light is measured by means of instruments called *photometers*.

A clean grease spot on a sheet of paper becomes visible when held between the eye and a source of light, because more light comes through the greased spot than elsewhere. When viewed by reflected light, it appears darker than the rest of the paper, because less light is thrown off from it. *If held between two sources of light, so that the paper is equally illumined on each side, the grease spot will disappear,* since it will then be no brighter than the rest of the paper. If the paper be moved toward either light, the spot will again appear. This is the principle of *Bunsen's photometer,* in which a grease spot is made in a sheet of paper supported in a frame. The paper is placed between two lights, and moved backward and forward until a position is obtained at which the spot disappears. The intensity of illumination is inversely proportional to the square of the distance. The illuminating power of the source of light is directly proportional to the square of the distance. When the paper has been moved until the grease spot has disappeared, it is equally illuminated on each side. The distance of the lights from the screen is now measured, and the illuminating power is directly proportional to the square of these distances. Call the two lights *A* and *B*, Fig. 113, and suppose the screen to be one foot from *A* and two feet from *B*, then *B* has four times the luminous intensity of *A*.

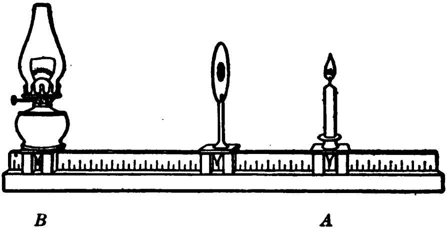

FIG. 113.

264. Standard Candle.—Candle Power.—In order to compare the intensity of different sources of light, a standard of comparison, such as a *standard candle*, is adopted. A standard candle is the intensity of light given out by a candle of given composition, that will burn at the rate of 120 grains per hour, or 2 grains per minute (0.1296 gram per minute).

In photometric measurements the intensity of the light to be measured is obtained in terms of a standard candle. The number of standard candles or fractions thereof that it equals is called its *candle power*.

265. Images Formed by Small Openings.—If the light from brilliantly illumined objects be allowed to come through a small opening into a dark room, and fall on a white screen, as in Fig. 114, there will be formed on the screen a distinct image of the objects from which it came. The image will have the same colors as the object, but its size will depend on the distance of the screen from the opening.

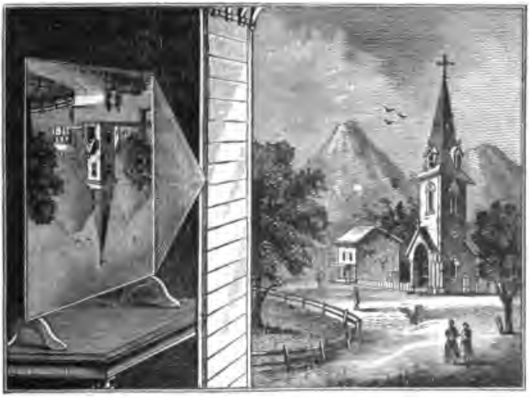

FIG. 114.

The diffused light, coming from all points of the object, enters the opening and produces on the screen an exact representation of the parts from which it came. As, however, the rays cross at the opening, the light from the top parts of the object will be received on the lower parts of the screen, and those of the lower parts of the object will be received on the top parts of the screen; *the image will, therefore, be inverted.*

Experiment 61.—Allow the sunlight to pass through a hole in the shutter of a darkened room, and fall on a piece of white paper held at right angles to the direction in which the light is entering the room. Observe the round disk of light that will be seen on the paper. This is the image of the sun.

Experiment 62.—Place a smooth piece of tin-foil over the hole in the shutter. Punch a hole in the foil with a large pin or needle, and allow the diffused light from the trees, houses, or other objects outside to fall on a screen held opposite the pin-hole. Observe the inverted image of the objects outside that will be seen on the paper.

Experiment 63.—Unsolder the top from an empty tomato can by holding it in the flame of a Bunsen burner, and punch a hole in the bottom with a nail. Paste a piece of tin-foil over the nail-hole, and make a pin-hole in it. Cover the open end of the can with a piece of oiled paper. Bring a lighted candle near the pin-hole and observe the inverted image of the candle that will be seen on the paper.

266. Shadows.—When light falls on an opaque body, the space immediately behind the body, into which no light penetrates, is called a *shadow*.

Shadows result from the fact that light moves in straight lines, and is not perceptibly bent on passing the edges of opaque bodies.

If a luminous point, *s*, Fig. 115, be placed near an opaque body, *A*, the light falling on the opaque body will illumine the parts nearest it, but, grazing the edges of the body, as at *a* and *b*, the light will continue moving in sensibly the same straight lines, *s a* and *s b*, in which it came from the luminous point. If the luminous point come nearer the opaque body,

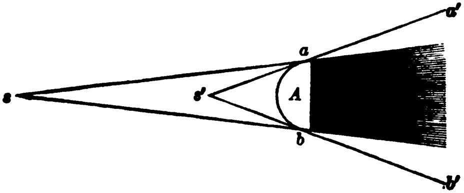

FIG. 115.

as at s', the shadow becomes larger, being now bounded by the lines $s'\ a\ a'$ and $s'\ b\ b'$. The *shape of a shadow*, therefore, is dependent on the *shape of the opaque body*, and the *size* of the shadow on the *distance* of the luminous point from the opaque body.

When the luminous body has an appreciable size, as at *S*, Fig. 116, only a part of the shadow is complete, viz.: that lying within the conical space *a o b*. As we pass outside this space, the shadow is less complete, since these portions are illumined by the light coming from the edges *c d* of the luminous body. That part of the shadow lying within *a o b*, into which no light penetrates, is called the *umbra* or *complete shadow;* that lying without these lines, as far as *a f* and *b g*, is called the *penumbra* or *partial shadow*.

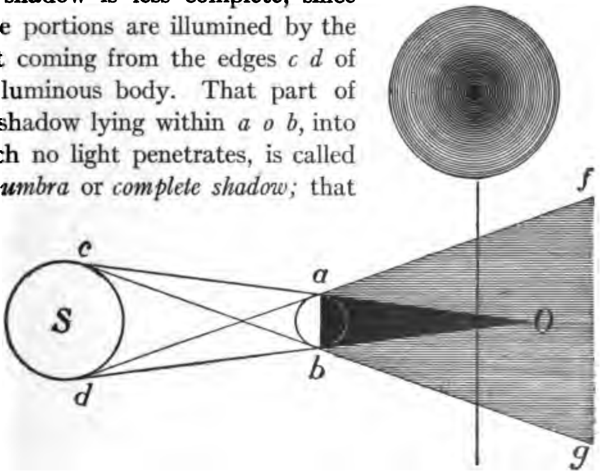

FIG. 116.

Experiment 64.—Hang a wet sheet from the ceiling or preferably in an open doorway, so as to act as a curtain or screen. Place a lighted candle on the floor back of the sheet, and then walk backward and forward between the sheet and the candle, and observe the curious and grotesque shadows that appear to those on the other side of the sheet. While walking toward the candle, the shadows rapidly increase in size, and, while walking away from it, rapidly decrease. By stepping over the candle, the shadows appear to be leaping through the ceiling.

267. Velocity of Light.—Light moves with the enormous velocity of about 186,000 miles (300,000 kilometres) a second. This velocity would, in one second, carry light over a distance greater than seven times around the earth at the equator. For all distances on the earth at which objects are visible we may, therefore, regard the transmission of light as instantaneous.

The first determination of the velocity of light was made by Römer, a Danish astronomer. He observed in 1675 that the interval between successive eclipses of one of Jupiter's satellites was slightly longer when the earth was at E_2 than when the earth was at E_1. When the earth is at E_1, its orbital motion is parallel to that of Jupiter, and during the interval between two eclipses (about two days) the distance between the two planets is but slightly altered. When the earth is at E_2 its orbital motion is carrying it almost away from Jupiter with a velocity a little more than 18 miles per second. So that at the second of two successive eclipses when the earth is in the position E_2, it would be over 3,000,000 miles farther from Jupiter than at the first of the pair of eclipses. The stream of light from Jupiter to the earth is then 3,000,000 miles longer at the second than at the first eclipse. Since the satellite will remain visible to an observer on the earth until the end of the stream of light reaches him, the longer the stream of light, the more will the eclipse be

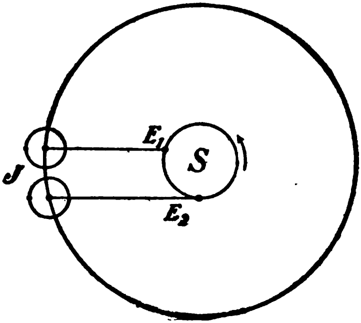

FIG. 117.

delayed. In September, 1676, Römer announced that a particular eclipse in November would be ten minutes later than the time predicted from the observed interval between the two successive eclipses in August. If E_1 is the position of the earth in August and E_2 in November, the difference between the distances from the earth to Jupiter will be about equal to the radius of the earth's orbit. So that Römer's statement meant practically that light required ten minutes to travel a distance equal to the earth's orbit. We know now the time to be 8 minutes and 19 seconds.

Fizeau, in 1849, determined the velocity of light by measuring the time required for light to travel a known distance on the earth's surface. Foucault, in 1850, found that the velocity varies with the medium in which the light travels. Michelson and Newcomb, in this country, repeated the work and obtained as their final results a velocity slightly less than 300,000 kilometres per second.

The velocity of light varies with the nature of the medium and with the color. In water, the velocity is about 140,000 miles per second, and in glass, about 125,000 miles per second.

268. Actions which Take Place at the Surface of Bodies.—When light falls on a body, it either passes into the body, or is thrown off from its surface.

The light which is thrown off from the surface is either *reflected* regularly or diffusely.

The light which passes into a body may pass through it if the body be translucent or transparent. In this case the direction of the light may be changed on entering the body, and the light is said to be *refracted*. When the light which enters the body does not pass through it, the light is said to be *absorbed*.

269. Diffusion of Light.—When the light which falls on the surface of a body is thrown off from it in all directions, or irregularly reflected, it is said to be *diffused*. Illumined bodies are visible by means of the diffused light which they throw off in all directions.

270. Absorption of Light.—Ether waves that are *absorbed* by a body cause its molecules to vibrate, *i. e.*, warm the body. When a surface absorbs most of the light which falls on it, the surface appears black or dark, because it diffuses but little light. No surface absorbs all the light which falls on it, since we know of no bodies so black as to be invisible.

271. Phosphorescence.—Phosphorescent bodies are those that, when exposed to a bright light, will continue to shine for some time after they are taken into the dark. The ether waves, in being absorbed, impart their energy to the molecules, and this is afterward liberated as light.

The faint light emitted by glow-worms, fire-flies, and jelly-fish, or by decaying animal and vegetable substances, is sometimes called phosphorescence. This is quite different from the phosphorescence just described, and is due to the slow oxidation of a substance produced by the animal, or which results from the decomposition of decaying animal or vegetable matter.

PROBLEMS

1. The nearest fixed star is said to be 25×10^{12} (25,000,000,000,000) miles from the earth. How long does it take light to come from this star to the earth?

2. What part of the light given out by a lamp does a board 10 cm. square and 25 m. distant from the lamp receive?

3. A 9-candle-power lamp and a candle are placed 4 m. apart on a photometer bar. Where must the screen be placed between them that it may be equally illuminated by each?

4. If the shadow of a flagpole is 25 ft. long, when a rod 4 ft. long casts a shadow 1.3 ft. long, how high is the pole?

5. When a screen is placed 9 in. from a hole in a shutter of a

dark room, the image of a chimney 60 ft. away is seen to be 6 in. high. How high is the chimney?

6. On a Bunsen photometer the candle was 8 cm. from the screen when the lamp was 42 cm. away. Find the candle power of the lamp.

7. Two lights of 4 candle power and 28 candle power are 3 m. apart. Where must a screen be placed between them to be equally illuminated by each?

8. The moon is 24×10^4 miles and the sun 92×10^6 miles from the earth. If the sun were as near to the earth as the moon, how much stronger would sunlight be?

CHAPTER XV

THE REFLECTION OF LIGHT

272. Reflection of Light.—When light falls on the surface of a body, it is thrown off from it at an angle equal to that at which it strikes the surface, and is said to be *reflected.*

273. Laws of the Reflection of Light.—1. *The angle of reflection is equal to the angle of incidence.*

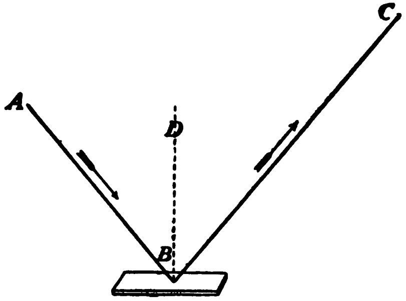

FIG. 118.

Let a ray of light *A B*, Fig. 118, fall on a reflecting surface, such as a piece of looking-glass, at the point *B*. At this point draw the perpendicular *D B*, then *A B D* is the *angle of incidence*, and *D B C* is the *angle of reflection.*

2. *The incident ray, the perpendicular at the point of incidence, and the reflected ray, all lie in the same plane.*

Thus, if the incident ray *A B*, and the perpendicular *D B*, lie in the plane of the paper, the reflected ray *B C* will also lie in the plane of the paper.

274. Amount of Light Reflected.—The amount of light reflected at any surface depends:

(1) *On the kind of material forming the surface.*
(2) *On the degree of polish of the surface.*
(3) *On the angle at which the light strikes the surface.*

Highly polished metals and glass are excellent reflectors of light. Transparent substances, such as glass or water, reflect the greatest amount of light the more obliquely the light falls on their surfaces. When light falls on such surfaces at nearly right angles, most of the light passes through the body. When the sun is nearly overhead, we may look at his image in a water-surface without being dazzled, because so little of the light is reflected; but when the sun is nearly setting, the image is too dazzling to be looked at steadily.

275. Mirrors and Specula.—A highly polished body, having a regular surface, and capable of reflecting most of the light which falls upon it, is called a *mirror* or *speculum*. These are made of glass, or other transparent medium, covered on the back with some good reflecting surface or of a highly polished metal called speculum metal. They may be either *plane* or *curved*.

276. Images Seen in Plane Mirrors.—When an object is placed in front of a plane mirror, an image, of the same size as the object, will be seen as far back of the mirror as the object is in front of the mirror.

We always see an image or an object in the direction in which the rays of light coming from it enter the eye. If, therefore, an object, such as a candle, *A B*, Fig. 119, is placed before the plane mirror, *C D*, the image will be seen by an eye at *P*, as though the candle were at *A′ B′*, back of the mirror. Every point of the object, as *A*, sends a cone of rays to the mirror, but when reflected, only a part of the rays enter the eye. This point of the image will appear to be situated back of the mirror where these rays apparently meet.

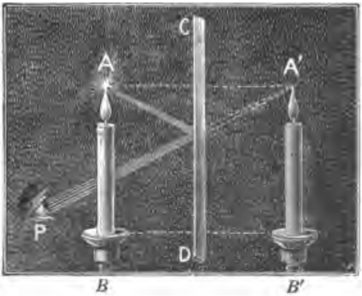

FIG. 119.

The image that appears back of the glass and which is formed by rays which do not come directly from the object is called the *virtual image*, because there is no real image back of the mirror. The rays of light do not actually diverge from the point A', but only appear to do so. As will be seen later, with a concave mirror an image can be obtained from which the light really comes to the eye. Such an image can be caught on a screen and is known as a *real* image.

The construction of the image of an object in a plane mirror may be shown, and its distance behind the mirror determined as follows:

Let A (Fig. 120) be a luminous point whose image in the mirror $M\ M'$ is to be found. Let two rays be chosen whose path, after reflection, may be predicted. Let $A\ X$ be one ray. As it is perpendicular to the mirror, the angle of incidence is zero, and, therefore, the ray is reflected back in the same direction. Let some other ray, $A\ Y$, be chosen. At the point of incidence, Y, erect the perpendicular $Y\ Z$. Then the angle of incidence is $A\ Y\ Z$. Draw the line $Y\ C$, making the angle of reflection $C\ Y\ Z$ equal to $A\ Y\ Z$. The rays $X\ A$ and $Y\ C$ are diverging and, therefore, will not meet on the side of the mirror from which the light came. There can, therefore, be no *real* image of the point A. But if the lines are prolonged back of the mirror, they will meet at the point A', which is, therefore, the *virtual* image of the point A. We wish now to prove that A' is as far behind the mirror as A is in front. The angles $A\ Y\ Z$ and $C\ Y\ Z$ are equal by construction. Therefore, $A\ Y\ X$ and $C\ Y\ M'$ are equal. But since the opposite angles $A'\ Y\ M$ and $C\ Y M'$ are equal, we have angles $A\ Y\ X$ and $A'\ Y\ X$ equal. The two triangles, $A'X\ Y$ and $A\ X\ Y$, being right angled at X, are, therefore, equiangular. Since they have the side $X\ Y$ in common, they are equal and $A'X = A\ X$.

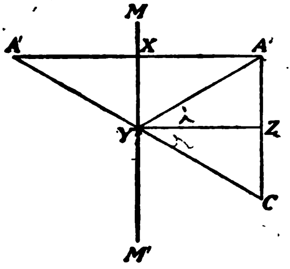

FIG. 120.

Plane mirrors cause the image to appear perverted, that is to say, the right-hand side of the body appears on its left, and the left-hand side appears on the right.

Experiment 65.—Write on a sheet of paper, and before the ink dries press a piece of clean blotting-paper on the writing, and observe that on removing the blotter it will have a copy of the writing reversed from right to left, just as a mirror appears to reverse objects; hold the blotter in front of a looking-glass, and the writing on the blotter can easily be read in the glass.

277. Apparent Position of Visible Objects.—No object is visible unless all its points give off diverging pencils of light. An object looked at directly is seen by means of these diverging rays entering the eye. We see the image of an object in a mirror, by means of the diverging rays it gives off, which enter the eye not directly from the object, but after reflection from the mirror, and each point in the image appears to be situated at the point from which the *visual rays*, or those entering the eye, appear to diverge.

The fact that the eye sees an image in the direction in which the rays enter it may be amusingly shown as follows:

Experiment 66.—Place four small pieces of looking-glass at *a*, *b*, *c*, and *d*, in the positions shown in Fig. 121. A ray of light from a distant object will, after reflection from the mirrors, enter the eye at *C* in the same direction as that in which it came from the object. Observe that the eye will see the object, although an opaque substance, such as a brick, be held at *B*, between the eye and the object, thus making it appear as though the person was seeing through the brick. The mirrors may be concealed in a suitably shaped box, with openings at *A* and *C*.

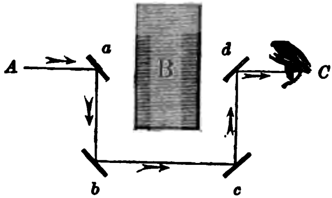

FIG. 121.

278. Multiple Images.—When any object is placed between two plane mirrors inclined at an angle to each other, a number of images will be seen, which will be the greater as the inclination between the two mirrors is less. This multiplication of the image of an object is seen in the *kaleidoscope*.

Experiment 67.—Place two looking-glasses or pieces of glass at any angle with each other, and observe the images of an object placed between them. Now change the inclination of the mirrors, and observe the change in the number of images.

279. The Visual Angle.—The rays of light which come from opposite extremities of an object form an angle at the eye called the *visual angle*. We judge of the size of an object by means of the visual angle combined with an estimate of its distance; the larger the visual angle, the larger the object appears. Thus, in Fig. 122 the visual angle under which the eye sees the object A A is $A\ O\ A$. If, now, the object is carried to A' A', it will be seen under the smaller visual angle $A'\ O\ A'$, and will, therefore, appear smaller.

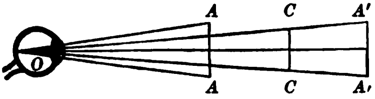

FIG. 122.

280. Curved Mirrors.—For many purposes it is desirable to use mirrors whose surface is not plane. *Concave* mirrors are curved like the *inside* of a watch crystal. *Convex* mirrors are curved like the *outside* of the crystal.

When rays of light from illumined objects enter the eye after reflection from curved mirrors, the visual angle under which the eye views the image is usually different from what it would have been had the eye viewed the object directly. *The apparent size of the images, therefore, is different from the apparent size of the objects.*

A concave mirror may be considered as a portion of the inner surface of a sphere. If we let $D\ B$ (Fig. 123) represent the mirror, then C, the centre of the sphere, of whose surface the mirror is a part, is called the *centre of curvature*. The line $C\ A$ passing through C and A, the centre of the mirror, is called the *principal axis*. Any of the lines passing through C and meeting the mirror, as $C\ B$ and $C\ D$, are called *secondary axes*. The angle $B\ C\ D$ is called the *angle of aperture* of the mirror. If the angular aperture is small, a point F, approximately half way between C and A, is called the *principal focus*. A focus is

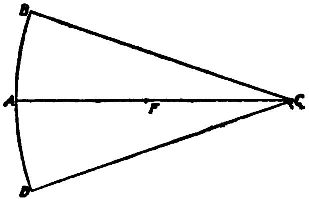

FIG. 123.

a point to which rays of light are brought after reflection by the mirror.

281. Action of Concave Mirrors.—In a plane mirror the image is always erect and virtual, and is found as far behind the mirror as the object is in front. In a concave mirror the properties of the image depend upon the position of the object. There are *six* different positions which the object may have with reference to a concave mirror, so that six cases must be considered. These will first be discussed with the object a luminous point.

To find the image of a point, it is necessary to find where two rays will meet after reflection. Two rays are chosen whose path can be predicted, and where these meet after reflection gives the image of the point.

(*a*) The point is at an infinite distance. All rays from an infinite distance will be parallel on reaching the mirror. Let one of the two chosen rays be along the principal axis. As this strikes the mirror normally, being a radius of the sphere, its angle of incidence is zero, and it is, therefore, reflected back on the path it came. If any other ray, as *D E*, Fig. 124, is chosen and the normal *C E* is drawn to *E*, the point of incidence, the angle of incidence is seen to be *C E D*. If now the angle of reflection *C E F* is made equal to this (Par. 273), the reflected ray *E F* meets the other reflected ray *A C* at *F*, a point half way between the centre of curvature and the mirror. The principal focus is, therefore, the image of the luminous point at an infinite distance.

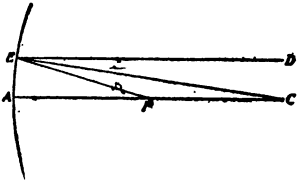

FIG. 124.

(*b*) The point is at the principal focus. This is evidently the reverse of *a*, for if we choose the two rays *F A* and *F E*, they will, after reflection, take the paths *A C* and *E D*, and will meet only at infinity.

(*c*) The point is on the principal axis at a finite distance beyond the centre of curvature. Let *P*, Fig. 125, be the luminous point and choose the two rays, *P A* and *P D*. *P A*, being the normal, is reflected back along *A P*. At *D* draw the normal *C D*, and then *D P′* becomes the reflected ray. *P′* is, therefore, the image of the point *P* and lies between the principal focus and the centre of curvature.

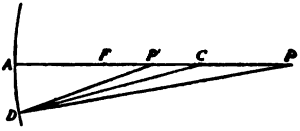

FIG. 125.

(*d*) The point is on the principal axis, between the centre of curvature and the principal focus. Let *P′* be the point. This is evidently the reverse of *c*, and the image of *P′* is found at *P* beyond the centre of curvature.

(*e*) The point is at the centre of curvature. All rays are now normal, and are, therefore, reflected back to *C*, so that the image and the luminous point coincide.

(*f*) The image is between the principal focus and the mirror. Let *P*, Fig. 126, be the luminous point, and draw the rays *PA* and *PD*. *PA* is reflected back along *AP*, being the normal. Draw the normal *C D*, and on making the angle of reflection *C D E* equal to *C D P*, the ray *D E* is seen to be divergent. It will, therefore, never meet the ray *A C* in front of the mirror, but if the line *D E* is prolonged back,. will meet it at the point *P′*. *P′* is, therefore, behind the mirror. This is a *virtual* image; that is, it is a point from which the rays *appear* to come. In all other cases the concave mirror forms real images, which may be caught on a screen, and are points from which the light really comes to the eye.

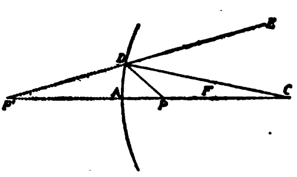

FIG. 126.

282. Images Formed by Concave Mirrors.—By applying the principles of Par. 280, it is seen that of the six possible cases of images formed by a concave mirror, five are real images and one virtual. By applying the rule of choosing two rays whose path can be predicted, the image of any object may be readily found. Two cases will be given: the others are entirely similar.

(*a*) The object is beyond the centre of curvature and at a finite distance. Let the arrow *D E*, Fig. 127, represent the object. Find first the image of *D* by drawing the rays *D H* and *D C*. *D H* being parallel to the principal axis, is reflected to *F*. *D C* passing through the centre of curvature is reflected back to *D*. Where these rays meet after reflection at *D′* is the image of *D*. In the same way *E′* is found to be the image of *E*. *E′ D′* is, therefore, the image of the object *D E*. It is real, inverted, and diminished. If the object is placed at *E′ D′* the image will be found at *D E*. The image will then be real, enlarged and inverted. When the foci are interchangeable in this way, they are called *conjugate* foci.

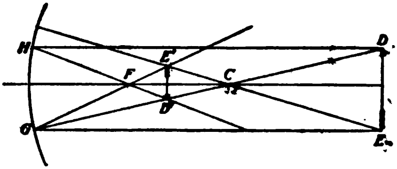

FIG. 127.

In the same way it is readily found that when the object is infinitely distant, the image is found at the principal focus, real, and diminished to a point.

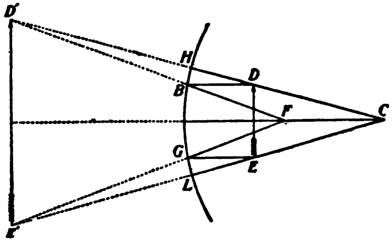

FIG. 128.

The remaining case, when the object is between the principal focus and the mirror, requires more special attention, although the method of construction is exactly as has been given before. To find the image of the point *D*, Fig. 128, the rays *D B* and *D H* are drawn. *D B* being a parallel ray, is reflected along *B F*. *D H* being a normal, is reflected along *H C*. These rays are divergent and, therefore, cannot meet in front of the mirror. If the lines are, however, prolonged back of the mirror, they will meet at *D′*, which is, therefore, the image of *D*. In the same way *E′* is found to be the image of *E*. *D′ E′* is, therefore, the image of *D E*. It is virtual, erect, and enlarged.

If the mirror is convex, Fig. 129, the image is always virtual, erect, and diminished. The rays after reflection cannot meet in front of the mirror, being divergent, but the lines meet when prolonged behind the mirror.

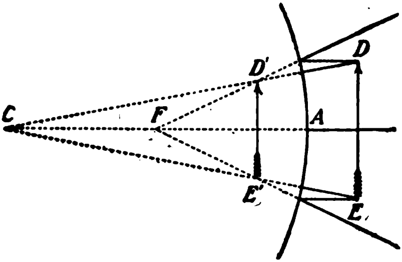

FIG. 129.—Convex mirror.

If the object, such as a candle, is placed before a concave mirror, at a shorter conjugate focus, an inverted and magnified image will be seen at the longer conjugate focus, as shown in Fig. 130, at *A;* but if the object is placed at the longer conjugate

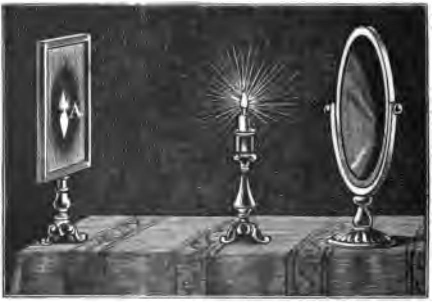

FIG. 130.

focus, the image will be inverted and smaller than the object, and will be seen at the shorter conjugate focus.

283. Equation for Mirrors.—If p = distance of the object from the mirror, and p' = the distance of the image from the mirror, and f = focal length of the mirror, then,

$$\frac{1}{p} + \frac{1}{p'} = \frac{1}{f}. \quad (32)$$

By this means the focal length of a mirror can be calculated from its conjugate foci. In the convex mirror p' and f are negative.

PROBLEMS

1. If the angle between the incident and reflected rays is 25°, what is the angle between the incident ray and the plane mirror?

2. Given a plane mirror and a rod 30 cm. long so placed that one end is 10 cm. from the mirror and the other 25 cm. away: construct the image of the rod.

3. An object is placed 20 cm. in front of a concave mirror. The image is found 80 cm. in front of the mirror. Find the focal length.

4. The principal focal length of a concave mirror is 30 cm. An object is placed 55 cm. in front of it. Find the position of the image.

5. A real image is formed by a concave mirror which is twice as large as the object. The focal length of the mirror being 25 cm., find where the object and image are situated.

6. An object is placed 15 cm. in front of a convex mirror, the radius of curvature of which is 40 cm. Where is the image? Of what size?

CHAPTER XVI

THE REFRACTION OF LIGHT

284. Refraction of Light.—When light falls on a water surface, part of the light is reflected, and part of it enters the water. Both in the air and in the water the light passes onward in straight lines. Thus, if a ray of light *D A*, Fig. 131, falls on a water surface at *A*, it is reflected in the direction *A E*, just as it would have been from any other reflecting surface. The part which enters the water takes the straight-line path *A G*. But the direction of the light in the water is not the same as in the air, the light being bent or *refracted* as it enters the water. This bending or refraction of light always occurs when light passes from one transparent medium to another of different density, unless the light falls perpendicularly on the surface, in which case it enters the medium without any refraction or change of direction.

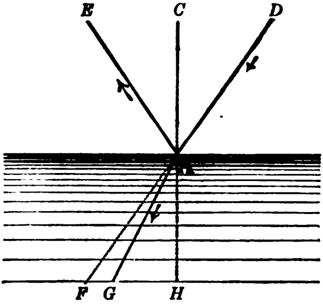

FIG. 131.

When light passes from a *rare* to a *dense* medium, as from air to water or glass, it is bent *toward* the perpendicular; when it passes from a *dense* to a *rare* medium, as from water or glass into air, it is bent *from* the perpendicular.

285. The Cause of Refraction.—The cause of refraction is the change of velocity in passing from one medium to another.

That the retardation of light in a denser medium causes refraction may perhaps be more readily understood by the following analogy: Suppose that an automobile while traveling over a smooth road meets a bad piece of road, but in such a way that both front wheels strike the rough road at the same instant. The automobile will be slowed up, but its direction will not be changed, as both wheels strike the rough ground at once. Suppose, however, it meets the rough ground at an angle. Then the wheel which strikes first is retarded and the other wheel gains on it, so that when both wheels are on the rough ground, the automobile has been changed in its direction. The amount of change of direction will evidently depend upon the roughness of the road. Applying this consideration to light, we see that when the wave front meets the second medium normally, it is retarded but not refracted, but that when it meets it at an angle, it is bent out of its course and refracted.

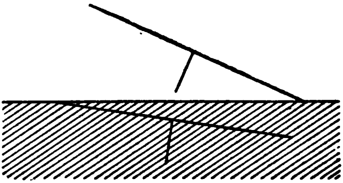

FIG. 132.

286. The Index of Refraction.—Let *D I*, Fig. 133, be a ray of light striking a water surface at *I*, and let a circle be described with radius *D I* about the point of incidence. Draw the lines *D N* and *P S* from the ends of the radii *I D* and *I S* at right angles to *N I P*, the perpendicular at the point of incidence. The ratio of *D N* to *S P* is called the *index of refraction* of the substance. Thus, if *D N* is 4, and *S P* is 3, the index of refraction will be $\frac{4}{3} = 1.333$.

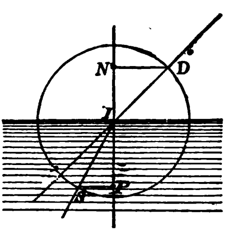

FIG. 133.

If *D N* is the *sine* of the angle of the angle of incidence, *D I N*, then *S P* is the sine of the angle of refraction, *S I P*. The index of refraction may, therefore, be defined as the ratio of the sine of the angle of incidence to the sine of the angle of refraction. This really means the ratio of the speed of light in air to its speed in the other medium.

The indices of refraction of some common substances are as follows:

Water	1.33	Crown glass	1.53
Alcohol	1.36	Flint glass	1.67
Carbon bisulphide	1.64	Diamond	2.47

287. Laws of the Refraction of Light.—

(1) *Light is refracted toward the perpendicular at the incident surface, when the ray enters a denser medium, and from the perpendicular when it enters a rarer medium.*

(2) *The incident ray, the perpendicular at the point of incidence, and the refracted ray, all lie in the same plane.*

(3) *Between the same two media the value of the index of refraction remains constant, whatever may be the angle of incidence.*

This last law is known as Snell's law, from its discoverer.

288. Effects Caused by Refraction.—The refraction which occurs when light passes from air to water may be shown as follows:

Experiment 68.—Place a coin *a* in the bottom of an empty bowl, *A*, Fig. 134, and stand in such a position, as at *c*, that the coin is just invisible. Observe the fact that the coin will become visible when one quietly pours clear water into the basin. This is because the rays of light, which just graze the edge of the basin, are bent as they pass out of the water, and, taking the direction *b c*, enter the eye of the observer, who sees the coin in the position *a′*.

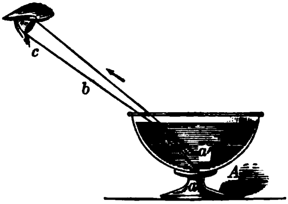

FIG. 134.

To an observer at *c*, Fig. 134, the coin *a* appears to be raised from its true position *a* to *a′*, when the bowl *A* is filled with water. This effect is produced when an observer in air looks at things in water, and is caused by refraction.

In Fig. 134 the diverging pencil of light is represented as coming from one point of the coin; when this light enters the eye, it appears to diverge from the point *a′*; consequently, we see the image of this point of the coin at *a′*, and not at *a*. Both the coin and the bottom of the vessel appear so raised that the water seems less deep than it really is, a circumstance which often causes errors of judgment as to the depth of clear water.

A stick, partly immersed in water, appears bent where it enters the water, because of the refraction of the light.

The light which comes from a distant star, situated near the horizon, suffers successive refractions as it enters the layers of air of increasing density near the earth's surface, so that after the star has really set, it is still visible for a short interval of time.

289. Effect of Refraction on the Apparent Position of Objects.—Since the position an object appears to occupy depends on the direction in which rays of light coming from it enter the observer's eye, and since refraction alters the direction of the light, it follows that, usually, the effect of viewing an object through refracting media of different density must be to change the direction in which it appears to be situated.

In order that this change in the direction of the visual rays by refraction may occur, the light from the object must pass through media of different densities, as, for example, when one looks at an object in the water, or when a medium of different density is placed between the eye of the observer and the object, as in looking at an object through a heavy plate-glass window.

290. Shapes of Refracting Media.—The high transparency of glass, the ease with which it may be cut or shaped into any desired form, and the power it has to bend rays of light out of their original direction have caused it to be generally employed in optical instruments where a marked change in the direction of the visual rays is desired to be obtained by refraction.

The change in the direction of light passing through a piece of glass held between the eye of the observer and any object at which he may be looking occurs both at the surface where the light enters the glass and where it leaves it.

When the sides are parallel, as in plates of glass, the object observed appears to be displaced to one side of its true position. In the same kind of glass, the amount of this displacement increases with the thickness of the glass.

When a ray *A B*, Fig. 135, strikes a piece of glass with parallel sides, it is bent toward the normal and takes the path *B E*. On emerging from the second surface into the air it is bent from the normal in the direction *E F*. Since the surfaces at incidence and emergence are parallel and the bending is the same at each surface, *E F* is parallel to *A B*, but displaced. This is readily seen by looking at some parallel lines through a piece of plate glass. When viewed at an angle, they remain parallel, but those seen through the glass are displaced as compared with those seen without the glass.

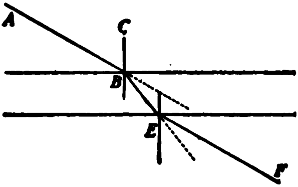

FIG. 135.

For exact details of this drawing, see Appendix.

291. Prisms. — When light passes through a triangular prism of glass, the surface where the light enters is not parallel to the surface at which it emerges, so that the emergent ray is not parallel to the entering ray. Let the candle shown in Fig. 136 be viewed through the glass prism. The light from any part of the candle is refracted, both on

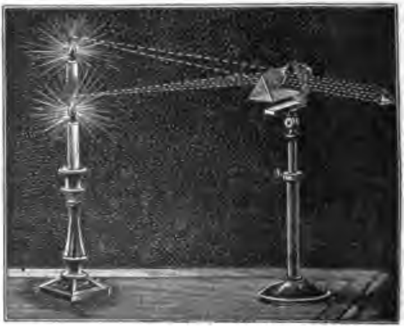

FIG. 136.

passing into the prism and on emerging from it. The observer, therefore, sees the object considerably out of its true position.

The amount of change produced in the apparent direction of an image by observing it through a prism depends on the nature of the material of which the prism is composed, on the amount of inclination of the faces where the light strikes and where it emerges, and on the angle at which the light strikes the prism.

When a ray of light $A\ B$, Fig. 137, falls on the surface of a glass prism, it is refracted toward the normal on entering the prism and takes the path $B\ D$. On leaving the prism it is bent from the normal and takes the path $D\ E$. The luminous object A, therefore, appears to be at A' on $E\ D$ prolonged.

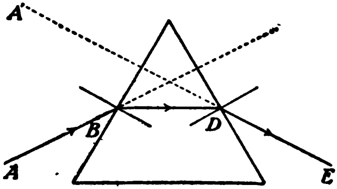

FIG. 137.

For exact details of this drawing, see Appendix.

292. Total Reflection.—When a ray of light passes from a more dense to a less dense medium, it is bent from the normal, that is, the angle of refraction is greater than the angle of incidence. As the angle of incidence increases, the angle of refraction approaches 90°. When this angle is reached, the refracted ray grazes the boundary of the medium. If the angle of incidence is increased, the light cannot enter the second medium, but is reflected back into the first medium. This phenomenon is known as *total reflection.*

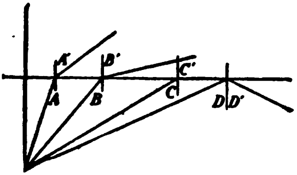

FIG. 138.

293. Critical Angle.—The angle of incidence, when the angle of refraction becomes 90°, is known as the *critical angle.* In Fig. 138, if light comes from some source under water, all the rays which strike the surface are refracted from the normal, except the one which is perpendicular. The ray forming the angle of incidence A is refracted to form the angle of refraction A', B

becomes *B′*, but when the angle *C* is reached, the angle of refraction *C′* is 90°. The angle *C* is, therefore, the critical angle, since the angle of refraction has become 90°. The critical angle for water to air is 48½°, for crown glass is 41°, and for the diamond is 24°.

294. Lenses.—A piece of glass, at least one of whose bounding surfaces is curved, is called a lens. Lenses are made in a great variety of forms. Those most generally employed are shown in Figs. 139 and 140.

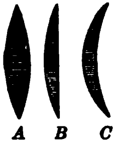

FIG. 139.

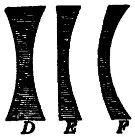

FIG. 140.

An examination of these figures will show that *A*, *B*, and *C* are thicker in the middle than at the edges; while *D*, *E*, and *F* are thinner in the middle than at the edges.

The first group *A*, *B*, and *C* are called *converging lenses*, because they cause parallel rays of light passing through them to converge. The second group, *D*, *E*, and *F*, are called *diverging lenses*, because they cause parallel rays of light passing through them to diverge.

These lenses are named as follows: *A is a double convex lens*, or more frequently a *convex lens; B* is a *plano-convex lens; C* is a *converging concavo-convex lens*, or, as it is sometimes called, a *meniscus; D* is a *double concave lens*, or, as it is more frequently called, a *concave lens; E* is a *plano-concave lens;* and *F*, a *diverging concavo-convex lens* or *meniscus.*

295. Foci of Lenses.—When sunlight passes through any form of converging lens, all the rays collect at a place called the *focus*. This is seen in the well-known experiment with a fairly large burning-glass, in which, on clear days, the focus at which the sensibly parallel rays of the sun collect is so hot that paper and wood are readily ignited. If the lens be held in front of the diverging rays from a gas-light or an electric light, the rays will also collect at a focus, which, however, will be situated at a different distance from the lens than that of the focus of parallel rays or sunlight. The position of the various foci of lenses depends on the shape of the lens, on the distance of the object from the lens, and on the kind of glass of which the lens is composed. With the kind of glass ordinarily employed and when the opposite faces of the lenses are equally curved, the positions of the foci are given in the following paragraphs:

The action of lenses on beams of light may be more readily understood if the action of prisms is recalled. If two prisms are put base to base, Fig. 141, and two rays of light parallel to the plane of the common base are allowed to fall on the two surfaces, the rays after transmission will be refracted so that they converge. This is the action of a double convex lens, which is converging.

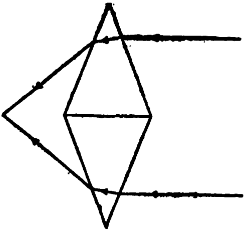
FIG. 141.

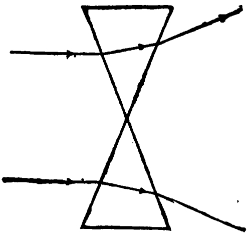
FIG. 142.

If the prisms are placed edge to edge, Fig. 142, the parallel rays are diverged on leaving the prisms. This is the action of a concave lens, which is diverging.

For details of the path of a ray in a lens, see Appendix.

296. The **Principal Focus** of any lens is its focus for sunlight or for parallel rays. Thus, in Fig. 143, the rays falling on the lens from its left-hand side are parallel, as they would sensibly be if they came from some object at a very great distance, as from the sun. These rays, after passing through the prism, meet at the point F, which is called the *principal focus* of the lens, or the focus of parallel rays. In the case of a double convex lens whose faces are of equal curvature, made of glass of index of refraction $\frac{3}{2}$, its principal focus is situated at about the centre of curvature of the face on which the light falls. Thus, in the case of the lens shown in Fig. 143, the principal focus F is situated, approximately, at the centre of curvature of the left-hand surface. The principal focus of a convex lens is a real focus; that is, the rays of light actually meet at this focus.

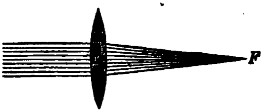

FIG. 143.

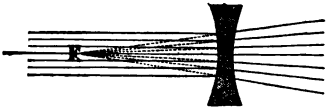

FIG. 144.

The principal focus of a double concave lens is situated near the centre of curvature of the face on which the light is incident with the same limitations as given above. Thus, in the concave lens shown in Fig. 144 the principal focus is at F, the parallel rays of light, after emerging from the lens, appear to diverge as though they came from F. The principal focus of a concave lens is a virtual focus; that is, the rays of light only appear to meet at this focus.

If a source of light be placed at the principal focus of a convex lens, the light will pass out from the lens sensibly parallel. This is the principle of the bull's-eye lantern, in which a candle or lamp is placed in a lantern at the principal focus of a convex lens supported in the side of the lantern. Such a lantern will throw a fairly strong beam of light a considerable distance, because the rays, being parallel, are not lost by being scattered, as are those of an ordinary lantern.

297. Conjugate Foci.—If the luminous point, instead of being at a very great distance, so as to produce parallel rays, be brought nearer to the lens, the diverging rays falling on the lens will, after passing through it, be brought to a focus at a distance further than the principal focus. Thus, the rays from the luminous point *C*, Fig. 145, are brought to a focus at the point *C′*, more remote from the lens than its principal focus. This focus possesses the property that if the luminous point be placed at *C′*, its rays falling on the lens will be brought to a focus at *C*. The points *C* and *C′* are, therefore, called *conjugate foci*, because they are interchangeable. All conjugate foci are real foci. *C* and *C′* are called respectively the longer and the shorter conjugate foci.

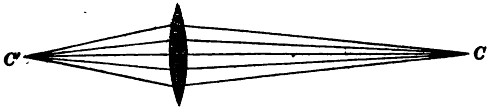

FIG. 145.

298. Virtual Focus.—If a luminous point be placed before a convex lens, nearer to the lens than its principal focus, as at *O*, Fig. 146, the rays, after emerging from the lens, will diverge as though coming from a point *V* on the same side of the lens as the luminous point, and at a greater distance from it than the distance of its principal focus. This is called the *virtual focus*.

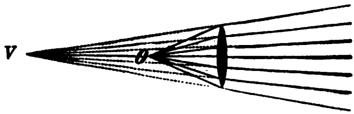

FIG. 146.

299. Cases of Convex Lenses.—As with concave mirrors, so with convex lenses, there are six possible cases.

(*a*) The object is at an infinite distance. The image is found at the principal focus, and is real, inverted, and diminished. Fig. 143 illustrates this condition.

(*b*) This is the reverse of *a*. The luminous point is at the principal focus, and the rays of light passing out as a parallel beam would never meet, or, as it is expressed mathematically, would meet at infinity.

(*c*) The object is further from the lens than twice its principal focal length. The method of construction is the same as for mirrors; *i. e.*, two rays are chosen whose paths may be predicted. Let *A B*, Fig. 147, be the object placed before the lens. *C* and *C′* are the centres of curvature of the two sides, and 2*C* and 2*C′* are the points at twice the focal length on each side. *O* is the optical centre of the lens. This point is so situated that the rays go through it without deviation, as the entering and the emerging sides of the lens for such rays are parallel. The rays chosen are *A X* parallel to the principal axis, and *A O* through the optical centre. After refraction these rays will meet at the point *A′*, which is, therefore, the focus of *A*. By the same means *B′* is found to be the focus of *B*. Therefore, *A′ B′* is the image of *A B*. It is a real, inverted, and diminished image.

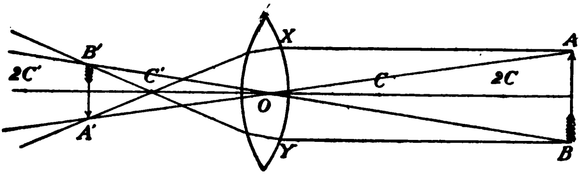

FIG. 147.

(*d*) The object is between *C* and 2*C*. This is the reverse of *c* and the method of construction is just the reverse of Fig. 147. The image is found at a finite distance beyond 2*C′* and is real, inverted, and enlarged.

(*e*) The object is, at 2*C*, twice the radius of curvature. The image is at $2C'$ an equal distance on the other side of the lens, and is real, inverted, and of the same size as the object.

(*f*) The object is between the principal focus C and the lens. This is the condition illustrated for a point in Fig. 146. For an object the construction is as follows: The rays chosen, Fig. 148, are the one parallel to the principal axis and the one passing through the optical centre. These will not meet at the other side of the lens, being divergent. If continued back, they meet at A', which is, therefore, the image of A. In the same way B' is found to be the image of B. A' B' is, therefore, the image of A B. It is virtual, erect, and enlarged. This is the action of a lens when used as a reading glass or as a simple microscope.

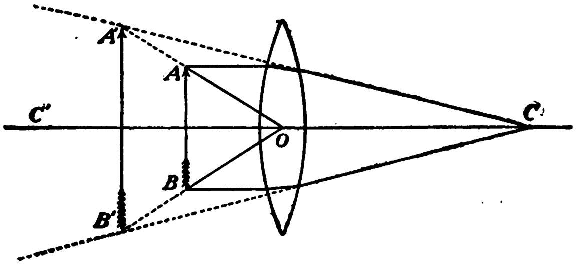

FIG. 148.

300. Equation for Lenses.—Let p = distance of the object from the lens, and p' = distance of the image from the lens, and f = focal length of the lens, then,

$$\frac{1}{p}+\frac{1}{p'}=\frac{1}{f}. \qquad (32)$$

With converging lenses, when so used that the image is virtual, p' must be considered as negative. With diverging lenses, both p' and f must be taken as negative. It will thus be seen that the focal length of a lens may be found by measuring its conjugate focal distances.

301. Defects or Aberrations of Lenses.—There are certain defects in lenses which prevent them from correctly reproducing, in the images they form, the outlines and colors of the objects. These defects are called *aberrations.*

Three of these aberrations may be mentioned:

(1) *Spherical Aberration.*—When the angular aperture of a lens is large, the portions of the lens near the edges have a different focus from the central portions; therefore, instead of a single image being formed by the lens, a number of separate images are formed alongside of one another at different distances from the lens.

(2) *Aberration of Sphericity.*—When a rectilinear object is placed before a lens, its extremities are at a different distance from the lens than are its central portions, and a curved image is formed. A sharp image would, therefore, not be formed on a flat screen.

(3) *Chromatic Aberration.*—The rays of light which pass through the edges of a single lens are often separated into different colors, just as they would be by a prism. The images formed by such a lens are incorrectly colored, being bordered by prismatic or rainbow-colored fringes.

Spherical aberration is caused mainly by the light which passes through the lens, at points near its edges. It may, therefore, be partially remedied by cutting off the portions of the lens near the edges by the use of a *diaphragm* or blackened plate of metal with a central opening, so that the light can only pass near the centre of the lens. It may also be remedied by certain combinations of lenses.

Chromatic aberration is avoided by the use of a double convex lens of crown glass, combined with a plano-concave lens of flint glass. Such a combination forms what is called an *achromatic lens.*

When several lenses of the same type, *i. e.*, both converging or both diverging, are combined or placed so that the light passes successively through them, the effect is to shorten the focal length. This device is frequently adopted in optical instruments, when it is desired to obtain a lens of short focal length with great breadth or diameter.

PROBLEMS

1. If the critical angle of a certain medium is 60°, find the index of refraction.

2. The critical angle of a certain medium is 45°; show that its index of refraction is $\sqrt{2}$.

3. An object 120 cm. distant from a convex lens gave an image 15 cm. from the lens. Calculate the focal length.

4. When the image formed by a convex lens is of the same size as the object, they are 80 cm. apart. What is the focal length of the lens?

5. The lens in a camera has a focal length of 8 in. How far off must an object be in order that it may focus sharply on a sensitive plate 10 in. from the lens?

6. An object is placed 9 cm. in front of a convex lens, the focal length of which is 5 cm. If, now, the object is moved 1 cm. nearer the lens, what will be the distance traveled by the image?

CHAPTER XVII

VISION AND OPTICAL INSTRUMENTS

302. The Eye.—The human eye consists of a nearly spherical chamber, darkened on the inside and provided with two openings, one in front for the entrance of light, and one in the rear, for the entrance of a nerve called the *optic* nerve, which conveys the impressions of light to the brain, and thus enables us to see. On its entrance to the chamber of the eye the optic nerve is spread out into a delicate network of nerve fibres, in what is called the *retina*, shown in Fig. 149, at *K*. The retina acts as a screen, to receive the images formed by the lenses of the eye. At the opening in the front of the eye is a transparent substance *A* called the *cornea*, more convex than the ball of the eye. Behind the cornea, and forming the colored part of the eye, is a circular curtain *D*, called the *iris*. A circular aperture *C* in the middle of the iris, called the *pupil*, forms the opening through which light enters the eye. Immediately back of the iris is a

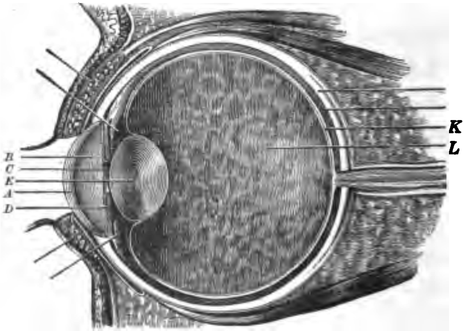

FIG. 149.

convex lens *E*, called the *crystalline lens*. The space *B*, between the cornea and the crystalline lens, is filled with a liquid called the *aqueous humor*. The large cavity *L*, behind the crystalline lens, is filled with a clear, jelly-like substance called the *vitreous humor*.

All these transparent portions of the eye act together as a single converging lens, and form an inverted and diminished image of a distant object on the retina. If the retinal image is sufficiently distinct, is properly illumined, and remains for an appreciable time on the retina, the object is seen distinctly. If too much light enters the eye through the pupil, the image is not seen distinctly. The eye, however, is so affected by light that if too much enters it, the pupil contracts and grows smaller; while if too little light enters, the pupil enlarges or dilates, and allows more light to enter.

Experiment 69.—Hang a small mirror immediately under a gas-light. Look in the mirror at the image of your eyes, and note the size of the pupil; now suddenly turn the light down, leaving only sufficient light to see the image. *The pupil will now be seen slowly to dilate.* Turn on the gas again and the pupil will be seen to contract.

303. Near-sightedness and Far-sightedness.—An object is seen distinctly only when the lenses of the eye cause a sharp image to fall upon the retina.

Some people have elongated eyeballs, so that the retina is farther from the cornea than in the normal eye. Such people are near-sighted, and can only see objects distinctly which are very close to the eye. The lenses of their eyes converge the rays so much as to cause the images of distant objects to be formed in front of the retina. *Near-sightedness can be remedied by the use of concave spectacles.*

Some people have flattened eyeballs, so that the retina is nearer the cornea than in the normal eye. Such people are far-sighted and cannot see distinctly. The lenses of their eyes cause the images of objects to fall back of the retina. *Far-sightedness can be remedied by the use of convex spectacles.*

304. Accommodation.—The extreme range of distinct vision extends from a few inches to an indefinitely great distance. Since, in order to see an object, its image must be focused on the retina, it is evident that when the eye looks at objects at different distances some change must occur which will have the effect of so altering the focal length of the eye as always to form a sharp image on the retina. This change is called *accommodation.*

Accommodation is accomplished principally by a change in the convexity of the crystalline lens. This change is brought about by the action of certain muscles.

The eye becomes *presbyopic* or far-sighted with age, owing to defect in accommodation; that is to say, the crystalline lens remains in its normal condition, adjusted for distant objects, and cannot change its convexity.

Fig. 150 represents a normal eye. In its passive condition, parallel rays, *i. e.*, rays coming from very distant objects, shown by the dotted lines, are brought to a focus at the retina, which is the principal focus of the eye.

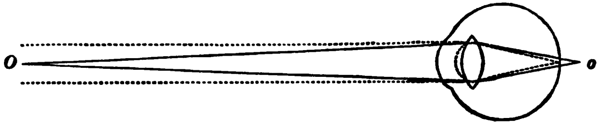

FIG. 150.

Rays from a nearer object, as at *O*, would be brought to a focus at the point *o*, behind the retina, so that no distinct image would be seen with such rays. The accommodation of the eye alters the shape of the crystalline lens, as indicated by the dotted lines, and makes it more converging, so as to bring the focus of the light from *O* on the retina. In old age this accommodation is lost, and convex glasses have to be worn in order to see distinctly.

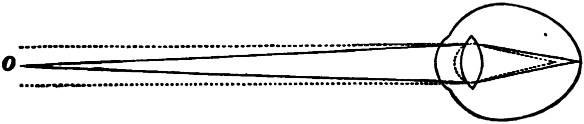

FIG. 151.

Fig. 151 represents the near-sighted, elongated eye. Here, in the passive condition of the eye, parallel rays are brought to a focus in front of the retina, while the rays from the near object *O* are then brought to a focus on the retina. Such an eye fails to see distant objects distinctly and can only accommodate itself to objects close by. It must, therefore, be aided by concave glasses.

Fig. 152 represents a flattened, far-sighted eye. Here, rays from a great distance, as well as from the nearer object *O*, would be brought to a focus behind the retina. Accommodation will bring the distant object to a focus, but not the nearer object. Such an eye cannot see near objects without convex glasses.

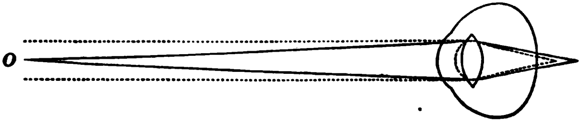

FIG. 152.

305. Images Formed by Lenses.—Whenever the visual angle under which the eye views an image formed by a lens differs from the visual angle under which the eye would view the object directly, the apparent size of the object will be changed.

If an object be held between the principal focus of a convex lens, and the lens, as at *A*, Fig. 153, an eye placed on the other side of the lens will see an erect and magnified image of this object, apparently situated farther from the lens than the object. The construction of this image is explained in case (*f*), Par. 299.

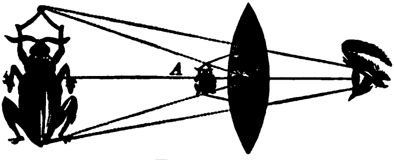

FIG. 153.

If we examine any object with a magnifying-glass, we shall find, if we move the object toward and from the lens without taking it farther from the lens than the principal focus, that the size of the image will vary, but that the image will be most distinct when the object is held at a certain distance from the lens. It can be shown that *this position lies very near the principal focus of the lens.* The image will then appear at the distance at which the eye sees the object most distinctly, that is, at its limit of distinct vision for that sized object. Since this limit of distinct vision varies with different persons, each person must hold the glass at such a distance from the object that the image formed shall be at his limit of distinct vision; *that is, he must focus the glass to suit his eyes.*

306. Images at Conjugate Foci.—If an object be placed before a convex lens, at a shorter conjugate focus, an *enlarged* and *inverted* image will be formed at its longer conjugate focus; but if the object be placed at the longer conjugate focus, an *inverted* and diminished image will be formed at the shorter conjugate focus. In Fig. 154 the object *A B* is placed at the longer conjugate focus of the convex lens *O*, and an inverted image, smaller than the object, is seen at *A′ B′*. As this image is real, it may be received on a screen as shown.

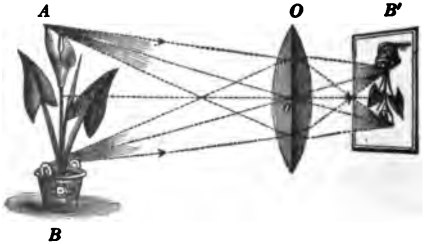

FIG. 154.

All images formed by convex lenses at their conjugate foci are real and are inverted. Those formed at the longer conjugate foci are magnified, and those formed at the shorter conjugate foci are diminished.

307. Optical Instruments are any combination of lenses, or of lenses and mirrors, that enable us to examine the images of distant or of near objects. Nearly all optical instruments employ more than a single lens, yet, so far as the production of the image is concerned, many of them act as though a single lens only were present; for example, the *simple microscope*, the *photographic camera*, and the *optical lantern* are optical instruments in which practically but a single lens is employed.

308. The Simple Microscope employs a single lens or combination of lenses, *A*, Fig. 155. The object to be examined is placed on a stage *C*, at a distance from the lens *A*, rather less than its principal focus. An eye placed above *A* sees an enlarged and erect image of the object. A screw *V* is used for focusing. The mirror *M* throws light on *C*. The action of the lens is explained in Par. 299, *f*.

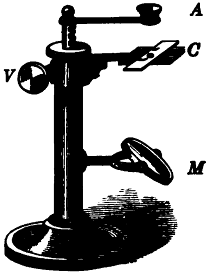

FIG. 155.

309. The Photographic Camera.—The photographic camera, Fig. 156, consists of a lens placed in a tube at *A* inserted in the camera box *G*. The image of an object, for instance, a person placed in front of a tube *A* at the longer conjugate focus is received on a screen of ground glass *E* as an *inverted* and *diminished* image. This image is sharply focused on the screen by means of the screw *D*. The screen is then removed and replaced by a plate covered on one face with chemicals sensitive to light. The image now falls on the sensitive plate, and is impressed upon it by the light causing certain changes in the chemicals covering its surface. In the use of the camera the object is

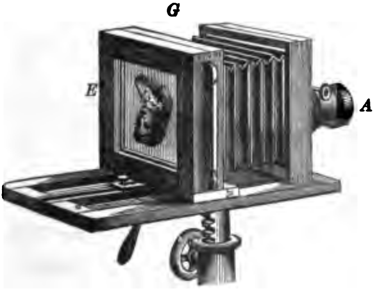

FIG. 156.

beyond $2C$ or at a longer conjugate focus, and the image is, therefore, formed between $2C$ and C, or at a shorter conjugate focus.

310. The Optical Lantern or Stereopticon.—This instrument, also called the magic lantern, is used to throw on a screen the image of an object, as a picture painted or photographed on a glass slide. The necessary parts are a strong source of light, a condensing lens, and a projecting lens. The most effective source of light is the electric arc. In front of the light is placed a combination of two plano-convex lenses, which collects the diverging rays from the arc and brightly illuminates the object placed at O. The objective D is so placed that O is at the shorter conjugate focus of the image-forming lens, that is, between C and $2C$. There is, therefore, found on the screen at the longer conjugate focus E, which is beyond $2C$, a real, inverted, and enlarged image. In order that the picture on the screen may appear erect, the slide must, therefore, be inverted in the lantern.

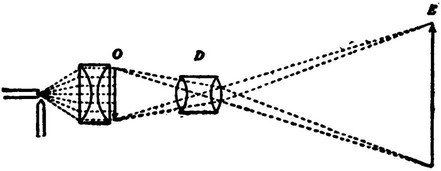

FIG. 157.

311. The Compound Microscope employs at least two lenses or sets of lenses, as shown in Fig. 158. Instead of looking directly at the object, the magnified image formed by one set of lenses is viewed through a second lens, which still further magnifies it. The lens which is placed nearer the object is called the *objective;* the lens nearer the eye is called the *eye-piece.* The object $b\ a$ is placed before the objective O, at a *shorter conjugate focus,* and an *inverted* and *enlarged* image formed by it at $a'\ b'$. The image *a′ b′* lies nearer to the eye-piece *C* than its principal focus. The eye, therefore, sees a greatly enlarged image at *A B*, which is inverted as compared with the original object.

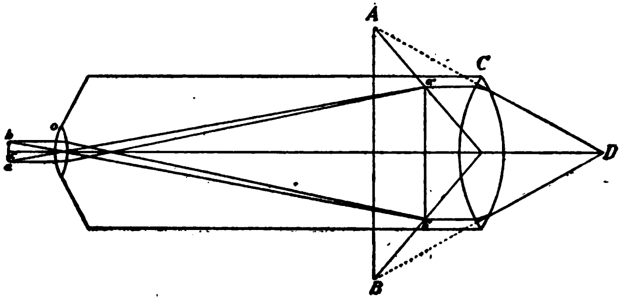

Fig. 158.

312. The Telescope, like the microscope, employs two lenses or sets of lenses; the lens nearer the object is called the *object-glass*, and that nearer the eye is called the *eye-piece*. Telescopes constructed with both object-glass and eye-piece of glass are called *refracting telescopes*. If a concave mirror is used in the place of the object-glass, it is called a *reflecting telescope*.

In the refracting telescope shown in Fig. 159 *O* is the object-glass and *E* the eye-piece.

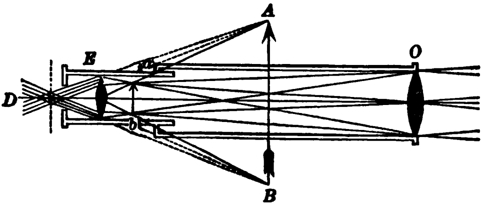

FIG. 159.

Since the telescope is used for viewing distant objects, *the object is necessarily situated at a longer conjugate focus.* Its image, therefore, seen at *a b*, is *inverted* and *diminished.* As in the microscope, this image falls within the principal focus of the eye-piece, and is, therefore, viewed by the eye placed at *D* as a magnified image *A B*.

The telescope owes its great penetrating power to the great size of the object-glass. The amount of light which can enter the unaided eye from a distant object is limited by the size of the pupil; but by the use of a telescope all the light which falls on the object-glass is swept into the eye. The penetrating power of the telescope will, therefore, be as much greater than that of the eye as the area of the object-glass is greater than the area of the pupil of the eye.

313. Binocular Vision.—When we look at an object, an image is produced on the retina of each eye. Under normal conditions these images produce the sensation of a single picture only. The image formed by the right eye is not identical with that formed by the left eye, but shows more of the right side of the object, while the image of the left eye shows more of the left side. The effect of combining both these images in a single picture is to give an appearance of solidity to the object. Vision obtained in this way by two eyes is called *binocular vision.* Besides producing the appearance of solidity, binocular vision aids us in forming an estimate of the relative distances of objects.

The stereoscope is a device for readily merging the images of two separate pictures into a single image, and so obtaining an appearance of solidity and perspective. The two pictures are taken from two slightly different points of view.

CHAPTER XVIII

COLOR

314. Dispersion of Light.—The Spectrum.—Just as the so-called simple notes of musical instruments seldom consist of a single tone, being accompanied by a number of additional or overtones, so sunlight, though apparently of one color, contains light of many different colors. If sunlight coming in the direction *F K*, through a narrow slit *F*, in the shutter of an otherwise darkened room, be allowed to pass through a prism *P*, as shown in Fig. 160, the light will not only be bent out of its course by refraction, but it will also be separated into a number of differently colored rays, which, if allowed to fall on a screen, will be spread out in the form of a brightly colored band *V R*, called a ***spectrum***.

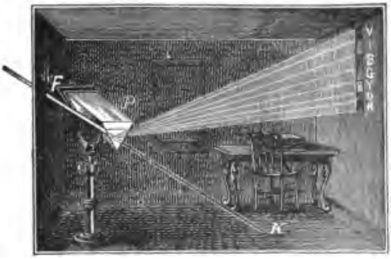

FIG. 160.

There is almost an infinite variety of colors in the spectrum of sunlight; but, for the sake of simplicity, we may distinguish seven well-marked regions of color, which are called violet, indigo, blue, green, yellow, orange, and red. The order of these colors may be easily remembered by the word ***vibgyor***, which is formed by putting together the first letters of the names of the colors.

The different colors of the spectrum are refracted in different degrees; thus, an inspection of Fig. 160 will show that the red is the least, and the violet the most, turned out of its course; in other words, the different colors of the spectrum differ in their refrangibility, red being the least refrangible, and violet the most refrangible.

The separation of light into different colors in this way by its passage through a prism is called *dispersion.*

The differences in color are due to the same causes as are the differences of tone or pitch of sound-waves; viz., to the difference in the frequencies, or the number of vibrations per second. The reds and oranges correspond to the grave tones, and the blues and violets to the shrill tones.

The range of sensibility of the eye to color is far less than that of the ear to sound, the eye being sensitive to rather less than one octave, while the ear is sensitive to about eleven octaves.

315. The Recombination of the Colors of the Spectrum.—When all the colors of the solar spectrum act at the same time on the eye, they produce the sensation of white light, like that of the sun. This may be shown by causing the spectrum to fall on a convex lens, or on a reversed prism, and allowing the light so collected to fall on a screen placed at the focus of the lens or in front of the prism. The spot of light formed on this screen will be no longer colored, but will be pure white.

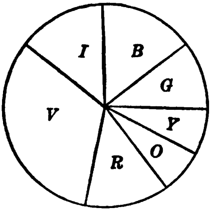

FIG. 161.

Experiment 70.—Cut out a disc of white cardboard, and paint on it, in spaces corresponding to those as shown in Fig. 161, seven colors, as near as can be obtained to those seen in the solar spectrum or the rainbow. Stick a pin through the centre of the disc, and whirl it rapidly around with the fingers, observing that, when it is turning fast enough, it will appear to be colored grayish white, from the mingling of the different color sensations.

316. Cause of the Dispersion of Light.—All waves of light, no matter what their frequencies, pass through free ether with the same velocity. Thus all colors of light emitted from the sun reach the earth in the same interval of time.

When the complex wave of white light enters the dense substance of a prism, the different wave lengths, or the different colors of light, are differently refracted, and, therefore, take separate paths; or, in other words, the white light undergoes dispersion.

Although different-colored lights move with the same velocity through the free ether, yet they move through the ether which occupies the space between the molecules of solids with different velocities. Each transparent solid has its own rate of transmission of light rays, and in the same substance this rate varies with the frequency.

317. The Cause of Color.—When sunlight falls on any colored body, as on a piece of red cloth, nearly all the colors of the light but the reds are absorbed, and these only being given off, the cloth appears red; so in a green leaf, all the colors but the greens are absorbed, and the greens only are given off. The colors of bodies are, therefore, due to the light which they reflect.

If a body of any color, such as pure red, be illumined by light which contains no red, the body will appear black. Thus, if a piece of bright red flannel be held in the pure green light of the solar spectrum, it will appear black.

Experiment 71.—Roll a piece of lamp-wick into a loose ball, and soak it for a few moments in a strong solution of table salt in water. Then place the wick in a saucer, pour some alcohol over it, and set fire to it. It will burn with a pure yellow light. Examine different colored objects, such as zephyrs, cloths, or silks, by means of this light, and observe that in an otherwise darkened room they will appear to have lost their colors, except those which are yellow. Now bring a lighted candle near any of the objects, and, since the lighted candle gives off light of all colors, the color of the fabrics will again appear.

The color of transparent objects is due to the light they transmit. A piece of red glass held in a beam of white light gives a beam of red light, because the other colors are absorbed and only red light is transmitted. If the same glass is held in the violet end of the spectrum, it cuts off all light, as there is no red light to be transmitted.

318. Theory of Color.—According to the Young-Helmholtz theory of color, the eye acts as if there were in the retina three sets of nerves by which color is observed.

The three primary senses of red, green, and violet may then be considered as conveyed to the brain by these three sets of nerves. All the various shades of colors, of which about ten thousand can be distinguished by a trained observer, can be obtained by a mixture of these primary colors in the proper proportions.

319. Color-blindness.—If one of the sensations of color is lacking, the person is said to be color blind. About 4 per cent. of men have this failure, which is organic and cannot be remedied. As the signals of railroads and ships are largely arranged on a color system, it is of great importance to be able to recognize this trouble.

By matching skeins of colored worsted Holmgren, of Sweden, has devised a means of detecting color-blindness.

320. Complementary Colors.—When all the colors of the spectrum are combined, white light is produced, but if one of the colors be removed, the mixture will no longer produce white. Thus, if the red is removed, from the spectrum, the admixture of the remaining colors will produce a shade of green. This green, if mixed with the red that was removed, will produce white light. Such a green is said to be the *complementary color* to the red, since it is what such red requires to complement or fill it to its full measure of white.

Experiment 72.—Complementary colors may be illustrated by a simple experiment which depends upon retinal fatigue. Look steadily for some time at a brightly illuminated red object on a black background. Then turn quickly and look at a white wall or screen. A green image of the object will now be seen. It is believed that, by continued use, the retina has become fatigued. When the white wall is viewed, the nerve terminals which respond to red are unable to respond, while all the other components of the white light produce the usual effect. Hence, one sees white light minus red and this is green, the complementary color.

Complementary Colors

Red	Greenish blue.
Yellow	Indigo blue.
Orange	Cyan blue.
Greenish yellow	Violet.
Green	Purple (compound color).

321. The Rainbow.—When sunlight passes through falling rain-drops, it is separated into its different colors, each rain-drop acting as a prism. On entering the drops, the light is reflected from the surfaces farthest from the sun, and passes out separated into its prismatic colors, having undergone refraction in passing through the drop. This light, entering the eye of an observer, standing with his back to the sun, causes him to see a band of colors called the *rainbow.* Rainbows are largest when the sun is near the horizon, as when nearly setting or shortly after rising.

322. Spectrum Analysis is based on the fact that the light given off by any gaseous or vaporous substance, heated to luminosity, is characteristic of that substance, that is to say, no two luminous gaseous or vaporous substances give off exactly the same kind of light. In order to determine the composition of a substance, it is, therefore, only necessary to reduce the substance to a gas or vapor, heat the gas or vapor until it emits light, and then examine that light.

But the unaided eye would not be able to detect all the differences in the light given off by different glowing gases or vapors, unless the different colors of such light were separated from one another by its passage through a prism. This is accomplished by the use of an instrument called the *spectroscope.*

323. The spectroscope consists of the following parts:

(1) A narrow slit in a plate so as to limit the amount of light which enters the spectroscope to a narrow beam.

(2) A collimator containing a converging lens, so that the light, after passing through the slit, forms a parallel beam before it reaches the prism.

(3) A prism or a number of prisms, through which the beam of light passes for the formation of a spectrum.

(4) A telescope with which to examine the spectrum so formed.

A form of spectroscope is shown in Fig. 162 and a diagram of the same instrument in Fig. 163. The substance is volatilized by the flame of a Bunsen burner *G*. For metals or other refractory bodies a stream of electric sparks is used. The narrow slit is placed in the tube *B* furnished with lenses, so as to cause the rays passing through the slit to fall on the prism *P* parallel to one another. The telescope *A* is used for the purpose of examining the spectrum. The telescope *C* is provided for the purpose of measuring the relative distances of the lines of the spectrum.

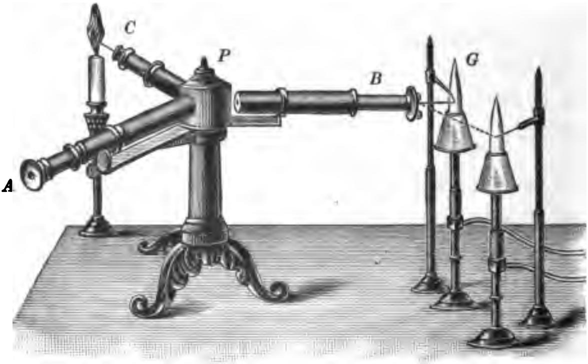

FIG. 162.

324. Fraunhofer's Dark Lines.—When the spectrum of a narrow beam of sunlight is examined, it is found to be discontinuous, numerous dark lines crossing it. These dark lines indicate places where certain frequencies of vibration are absent.

The dark lines of the solar spectrum were discovered by Wollaston in 1802. He failed, however, to recognize their importance. They were subsequently rediscovered by Fraunhofer, and are, therefore, named after him. The Fraunhofer lines are conveniently located in the spectrum by reference to eight prominent lines named A, B, C, D, E, F, G, and H.

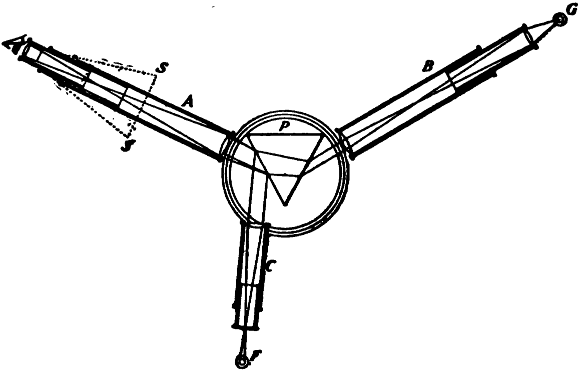

FIG. 163.

The frequencies and wave lengths, in hundred-millionths of a centimetre, of these lines may be seen in the following table:

NAMES.	Frequencies per second.	Wave-lengths in microns or millionths of a metre.
Line A	394,500,000,000,000	0.7604
Line B	436,900,000,000,000	0.6867
Line C	457,200,000,000,000	0.6562
Line D (middle of pair)	509,200,000,000,000	0.5892
Line E	569,300,000,000,000	0.5269
Line F	617,900,000,000,000	0.4861
Line G	696,500,000,000,000	0.4307
Line H	762,800,000,000,000	0.3933

325. Solar spectroscopic analysis is based on the presence of the Fraunhofer dark lines.

A luminous gas or vapor is opaque to light of the same frequency as that it is itself emitting. This fact is known as *Kirchhoff's law.*

Burning sodium, for example, emits a characteristic yellow light, which will permit all the colors of light of a continuous spectrum, except its own, to pass through it. If, therefore, the light from the crater of an electric arc be passed through the flame of a Bunsen burner in which sodium is burning, its spectrum will show the absence of the particular color of yellow the sodium vapor itself emits; or, in other words, a dark line will appear at this part of the spectrum.

The portion of the spectrum where this line occurs is not absolutely devoid of light, since the yellow light from the faintly luminous flame is present; but, by contrast with the brighter light of the electric arc, it appears dark.

326. Cause of the Fraunhofer's Dark Lines.—The Fraunhofer lines are absorption lines. The central body of the sun gives a continuous spectrum, but while the light is passing through the masses of glowing gases and vapors which surround the body of the sun, a selective absorption occurs, and that light which is of the same color as the light these gases emit is stopped or absorbed, and thus the dark lines are formed.

The spectroscope shows the portions of the spectrum in which these dark lines occur, and from this we infer the presence of such substances in the sun's atmosphere as would, when heated, emit light of the same color as that belonging to the parts of the spectrum where the dark lines are observed.

This selective absorption is due to the fact that the cooler outer regions of the sun's atmosphere absorb the energy coming from the interior. This is an example of sympathetic vibrations which were discussed under Sound (Par. 241).

327. Doppler's Principle Applied to Light.—Just as the apparent pitch of a sounding body changes as it moves toward or from an observer, so the apparent wave length of the light emitted by a star changes as it moves toward or from the earth. In this manner astronomers have been able to tell that certain stars are moving toward the earth and others from it. They have even been able to measure the velocity of this motion, in some cases about 150 miles per second.

Each bright line of a discontinuous spectrum is due to a particular wave length of light, and very many of these have been mapped and their position on a scale of comparison is known. In the spectrum of a star moving in the line of sight these lines will show a displacement, the amount of which may be measured by examining a comparison spectrum at the same time. If the lines are displaced toward the violet end of the spectrum, the wave length is shortened, because the star is moving toward us. If the displacement is toward the red end, the wave length is increased because the star is moving from us. From the amount of the displacement the velocity can be calculated.

328. Interference of Light.—The beautiful colors seen in soap bubbles, or in films of oil floating on water, are due to what is called the *interference of light.* We have already seen that when two separate sources of sound simultaneously affect the same particles of air, they may either augment or diminish each other's intensity, and that, under certain conditions, one may entirely annul the action of the other. The same is true with light. In the case of a soap-bubble or a thin film of oil, the light directly reflected from the surface of the film interferes with the light which is reflected from its lower surface. In certain portions of the film some of the colors in these rays completely obliterate one another, thus leaving the remainder of the light visible as rainbow tints. Similar effects of interference are seen in mother-of-pearl, and in the wing-cases of certain beetles.

Experiment 73.—Insert a thin piece of paper between the ends of two strips of glass and clamp the other ends firmly together. This will inclose a very thin wedge of air between the strips of glass, as shown in Fig. 161.

Look at the image of the flame in the strips in some source of monochromatic light, as that produced by introducing sodium chloride or carbonate into the flame of a Bunsen burner. Alternate bright and dark bands will be produced, due to the interference of the light as it is reflected from the different surfaces of the glass.

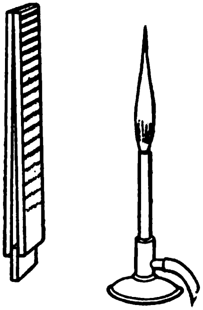

FIG. 164.

329. Diffraction.—The water behind a large post that projects above a water surface is not entirely shaded from small waves moving over the surface. A part of the energy in the wave is expended in producing what may be called *secondary waves*, which move in all directions from the post and thus partly disturb the water on the farther side. The same is true of light. When waves of light graze the sharp edge of a body, secondary waves pass into the geometrical shadow of the body. This phenomenon is called *diffraction*. Under certain circumstances these secondary light-waves may interfere with each other and thus produce prismatic colors, similar to those seen in the thin films.

A diffraction grating consists of a glass plate on which fine lines have been scratched very close together. These have been made with more than 25,000 to the inch. When a light is viewed through one of these gratings, the colors of the spectrum are seen.

330. Polarization.—When a sound wave travels in the air, the disturbance moves out from the sounding body by means of air waves, the shortest of which, perceptible by the ear, are about 0.8 cm. long. When a light wave travels, the propagation is by means of ether waves, the shortest of which are no longer than 0.00001 cm. But besides this difference in the medium and in the wave length, there is another fundamental difference. The sound wave is a longitudinal one, while the light wave is transverse. This fact, that the light wave is transverse, is proved by the phenomena of polarization, which can be most easily studied by means of the tourmaline tongs.

The tourmaline is a complex silicate often found in transparent crystals. These crystals act in a peculiar way toward light. If two slices are cut from a crystal and mounted in a holder, so that they can be rotated, the arrangement is known as the tourmaline tongs, as shown in Fig. 165.

If a beam of light is allowed to fall on one of the slices, it will pass through both if their axes are parallel, as shown in Fig. 166.

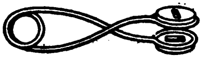

FIG. 165.

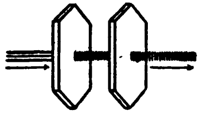

FIG. 166.

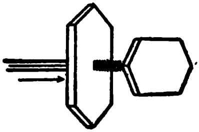

FIG. 167.

But if the second slice is turned so that its axis is at right angles to that of the first, it will not pass through, as shown in Fig. 167, so that darkness results.

When a stretched cord is set into vibration by moving one end up and down rapidly, transverse vibrations are produced. If a slit in a board is placed over the cord, the wave will pass through if the slit is parallel to the plane of vibration, but it cannot pass through if the slit is at right angles to the plane of vibration. The tourmaline crystal acts on the light wave as the slit does on the wave of the cord. The light which has passed through the first crystal and which cannot pass through the second is said to be plane polarized.

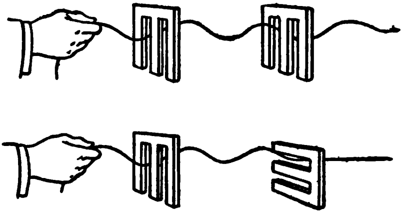

FIG. 168.

331. Double Refraction.—Some media, such as calc spar, possess the curious property of splitting up the rays of light that pass through them in certain directions into two separate rays, so that any object seen through them in those directions, such as the dark circle shown in Fig. 169, appears double. This effect is called *double refraction*, and is due to the fact that the substance possesses a different velocity of transmission of light in different directions. The rays from each image are polarized.

332. Actinism.—By actinism is meant the chemical effects of light.

Light possesses the power of causing various chemical decompositions. Photography is based on this fact. Silver chloride blackens on exposure to sunlight. The sunlight falling on the leaves of plants causes the decomposition of the carbonic acid gas which the leaves absorb from the atmosphere, the plant retaining the carbon, for the formation of its woody tissues, and throwing off the oxygen. The fading of carpets and tapestry is caused by the actinic power of light on their coloring matters.

FIG. 169.

A strip of paper, freshly washed in a solution of quinine sulphate, gives off a *fluorescent* light, that is, becomes momentarily self-luminous, when placed in different parts of a spectrum formed by a prism of quartz, which is transparent to the ultra-violet rays. This effect is found to be least in the red, and greatest in the violet, but extends far beyond the violet, thus showing the existence of an invisible spectrum of ultra-violet rays.

There is, therefore, said to be an invisible as well as a visible spectrum. Less refracted than the red end of the spectrum, heat effects may also be detected by a thermometer. This region is called the infra-red. Beyond the violet end, radiation may be detected by its chemical effect and these are called the ultra-violet rays. These ultra-violet rays are shorter in wave length than any of the visible rays. They have many peculiar properties, one of the most interesting of which is the healing effect upon certain diseases of the skin.

PART V

HEAT

CHAPTER XIX

HEAT AND TEMPERATURE

333. The Nature of Heat.—The molecules of all kinds of matter are never in a condition of rest, but are continually in rapid to-and-fro motions or vibrations. The hotter the body, the more energetic are these molecular vibrations. If matter were absolutely devoid of heat, these vibrations would be entirely absent.

As the temperature of a body increases, the rate at which the molecules vibrate increases; or, in other words, their kinetic energy becomes greater. If the temperature be raised sufficiently high, the body will glow and emit a red light. As the temperature increases, orange and yellow light accompany the red; and, at still higher temperatures, the other colors of the spectrum appear, and the substance becomes white hot.

The vibrating molecules of a heated body impart a wave motion to the surrounding ether, producing what is known as light and radiant heat. Radiant heat differs in no respect from light, save in the frequency of the vibrations. Ether waves, of frequencies between 392,000,000,000,000 and 757,000,000,000,000, produce on the eye the sensation of light. Ether waves of all frequencies produce the effect of heat, but higher or lower frequencies produce the effect of heat without light.

334. Heat as a Form of Energy.—In all cases a body becomes warmer when the energy of the to-and-fro motions of its molecules is increased.

Heat, therefore, is a form of energy, and, like all energy, may be measured in foot-pounds. A given weight of a substance, heated to a given temperature, possesses a greater amount of energy than if heated to a lower temperature. In other words, when bodies absorb heat, they acquire a greater store of energy; when they lose heat, they part with some of their energy. Heat energy is, therefore, a form of molecular energy. All bodies possess some heat energy.

Heat was formerly believed to be an imponderable fluid called *caloric*. According to this view, a body became heated when it absorbed or took in caloric, and grew cold when it threw it out. This view is now entirely abandoned. Heat is now known to be molecular motion.

In 1798 Benjamin Thompson, afterward Count Rumford, published the results of the experiment he had just finished at Munich. By means of the heat generated by the friction of a blunt steel borer in a cannon, he caused the temperature of a quantity of surrounding water to be raised. "At the end of two hours and thirty minutes the water actually boiled." "It is difficult to describe the surprise and astonishment," says Rumford, "expressed in the countenances of the bystanders on seeing so large a quantity of cold water (18¾ pounds) heated, and actually made to boil, without any fire." Reasoning that this production of heat *without limitation* showed that it could not be a material substance, he concluded that heat is a form of motion.

In 1799 Sir Humphrey Davy rubbed two pieces of ice against each other under the exhausted receiver of an air-pump, keeping the temperature below the freezing-point. Some of the ice was melted, from which he concluded that friction causes vibrations of the particles of the body and that this vibration is heat.

In the sun, heat energy is the energy of moving molecules. The heat energy of the sun is transmitted to the earth as *radiant energy; i. e.*, energy of wave motion in the ether. On reaching the earth, this energy is absorbed and becomes the energy of moving molecules, that is, heat.

Since heat has been defined as molecular motion, it is incorrect to speak of heat in circumstances where molecules are not present. The energy is transmitted from the sun to the earth by a wave motion of the ether. This is, therefore, not heat, but *radiant energy.* If the wave length is short enough for the eye to detect it, we call it light. If this energy is absorbed by any body so that its molecules vibrate more rapidly, we say the body has been heated. The term *radiant heat* is, therefore, used to mean those ether vibrations whose frequency is not great enough to affect the eye, but which, when absorbed by a body, produce heat. Of course, the light energy will also heat a body if absorbed by it. The terms dark heat and non-luminous heat are more objectionable terms formerly used to express this same idea.

335. Sources of Heat.—Our sources of heat on the earth may be classified under three heads, the sun and interior of the earth, mechanical actions, and chemical changes.

(1) The sun and the interior of the earth are both sources of large quantities of heat. The sun is the source of all the energy necessary to sustain both plant and animal life. Various suggestions have been made as to the cause of the sun's heat, such as its contraction, the falling of meteorites upon it from space, and more recently radio-activity. That the interior of the earth is highly heated is proved by various considerations, such as the continual rise of temperature as one approaches the centre in going down a deep mine. The action of volcanoes and geysers leads to the same conclusion.

(2) Whenever mechanical work is done, the energy employed is converted finally into heat. If a coin is rubbed briskly against the sleeve, heat is produced. All forms of *friction* produce the same effect. When a wrought-iron nail on an anvil is struck by a hammer, the *impact* produces heat. When the tire of a bicycle is inflated by means of a hand-pump the heating is very noticeable, produced in this case by *compression.*

(3) Whenever a chemical change takes place, there is an accompanying change of temperature. Usually heat is given out, though sometimes it is absorbed.

Experiment 74.—Pour some concentrated sulphuric acid slowly into some water. The temperature of the liquid will increase very greatly.

Experiment 75.—Place a small piece of iodine on a brick and lay on it a piece of yellow phosphorus. Very shortly the heat produced by the combination of these two elements will be sufficient to cause ignition.

Our best example of chemical change producing heat is ordinary combustion. Whenever coal or wood is burned, the heat produced is caused by the chemical change which has taken place as the oxygen of the air combined with the carbon and hydrogen of the fuel.

The temperature of our bodies is maintained by slow oxidation, the material for this being supplied by the food we eat and the required oxygen being breathed in by the lungs.

336. General Effect of Heat.—Although we cannot see the molecules vibrating in a body, yet we can see the effect which these vibrations produce. The hotter the body, the more energetic will be the motion of its molecules, and the greater will be the distance through which they move. In this way the force of molecular attraction is partially overcome, and the body expands. When a body loses heat, its molecular motion becomes less; attraction again draws the molecules together, and the body contracts.

337. Temperature.—When two bodies are placed near each other, each gives some of its heat to the other. If they are equally hot, each will give the other as much heat as it receives, and it will appear as if no heat passed between them. When no heat appears to pass between two bodies that are near each other, that is, when neither changes in size, they are said to be at the same temperature. If, however, one of the bodies is hotter than the other, it gives more heat than it receives, and, therefore, may be said to be at a different temperature.

The temperature of a body is measured by an instrument called a *thermometer*.

338. Thermometers generally depend for their operation on the expansion of a liquid contained in a glass tube. Mercury is usually employed for this purpose, though alcohol is sometimes used.

A thermometer consists of a long, straight tube, *A B*, Fig. 170, of small internal diameter, closed at the upper end, and widened at the lower end into a bulb *C*, preferably cylindrical in shape. The bulb *C* and part of the tube contain mercury; the space above the mercury in the tube has had the air expelled so as to produce a vacuum. When the thermometer is taken into a warmer place, the mercury becoming warmer, expands and rises in the tube; when taken into a colder place, the mercury, losing heat, contracts, and falls in the tube. The tube is graduated or marked off into equal spaces called degrees.

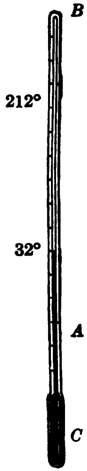

FIG. 170.—Fahrenheit.

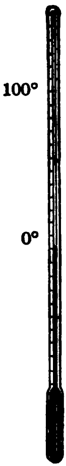

FIG. 171.—Centigrade.

339. Construction of a Thermometer.—Before the thermometer tube is closed at the top, the bulb and part of the tube are filled with cold mercury. The bulb is then carefully heated. As the mercury grows hotter, it expands, and, filling the tube, drives out all the air, and begins to flow over the top. The bulb is now taken away from the source of heat, and at the same time the upper end is completely closed by being melted in the flame of a blow-pipe. As the bulb cools, the mercury falls in the tube, leaving a vacuum or empty space above it.

The next step is the *graduation* of the tube, or its division into degrees. For this purpose the bulb is first dipped into melting ice, and a mark made at the point on the tube to which the mercury sinks. The thermometer is then exposed to the vapor rising from boiling water, and another mark made at the point to which the mercury rises. These two points are called respectively the *freezing point* and the *boiling point*. The length of the tube between the freezing and boiling points is then divided into a certain number of equal parts called *degrees*, and the remainder of the tube, that is, the part below the freezing point and above the boiling point, is similarly graduated, or divided into degrees of the same length.

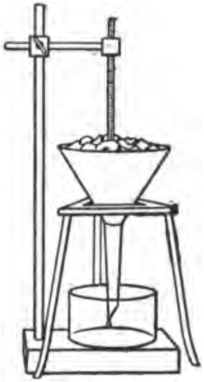

FIG. 172.—Freezing point.

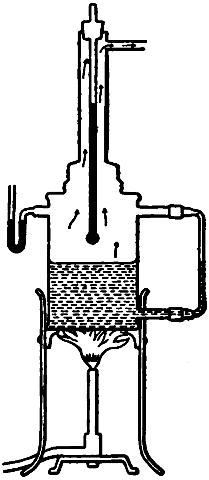

FIG. 173.—Boiling point.

There are two thermometric scales in common use: the *Fahrenheit* and the *Centigrade*. These two scales are represented in Figs. 170 and 171. In the Fahrenheit scale, Fig. 170, that length of the tube which lies between the freezing and boiling points is divided into 180 equal parts or degrees. The freezing point is marked 32°, and the boiling point 212°.

In the Centigrade scale, Fig. 171, the distance between the freezing and boiling points is divided into 100 equal parts. In this scale the freezing point of water is marked 0°, or zero, and the boiling point 100°. Degrees of the Fahrenheit scale are indicated by an F., or Fahr.; those of the Centigrade scale by a C. Thus, the freezing point of water is 32° F., or 0° C.

The zero of the Fahrenheit and the Centigrade scales is arbitrary. Absolute zero would, of course, be found when molecular motion absolutely ceases. Considerations based on the expansion and contraction of gases, and on other physical phenomena, estimate the absolute or natural zero of the thermometric scale at $-273°$ Centigrade or $-459°$ Fahrenheit. In the scale of absolute temperature, therefore, $-273°$ below the zero of Centigrade scale is taken as the absolute zero. Absolute temperature may be obtained by adding 273° to the indications of a Centigrade thermometer, or 459° to those of a Fahrenheit thermometer; thus water boils at 100° C., or 373° absolute temperature, or at 212° F. or 671° absolute temperature.

340. Uses of Thermometers.—We cannot rely on our sensations to determine accurately the difference between the temperature of two bodies. If the hand, while warm, is plunged into a basin of tepid water, the water will feel cool; but if the hand is cold when plunged into the same tepid water, the water will feel warm. Again, if in winter we come from the cold outside air into an entry or hall, the entry or hall feels warm; but if we go into the entry from the warmer parlor, then the entry feels cold. The indications of a thermometer are not open to these objections.

It is evident that hot and cold are only relative terms, since the same body may be hot when compared with one body, and cold when compared with another.

341. Expansion of Solids.—The general effect produced in all kinds of matter by an increase of temperature is to cause it to expand, while a decrease of temperature causes it to contract. Solids expand less than liquids, and liquids expand less than gases. Different solids expand differently in amount when heated one degree. Zinc, lead, and tin are among the most expansible of the metals, and steel and platinum among the least expansible. Ice is more expansible than zinc. Most crystalline solids expand more in one direction than in another, while most bodies that are not crystallized expand equally in all directions.

The change of length of a body when heated depends upon its length, the material, and the change of temperature. Therefore, the *expansion* = LKT. Here, L equals length of the rod, K is a constant depending upon the nature of the substance, and T is the change of temperature.

The new length L' equals the old length L plus the expansion, $L' = L + Exp.$

$$\therefore L' = L + LKT$$
$$= L(1 + KT). \quad (33)$$

The quantity K is known as the coefficient of linear expansion. It may be defined as the increase in length of unit length when heated one degree.

$K = \frac{L' - L}{LT}$. That is, the coefficient of linear expansion is equal to the change in length divided by the product of the original length and the change in temperature.

This may be determined as follows:

A cut of the necessary piece of apparatus is shown in Fig. 174.

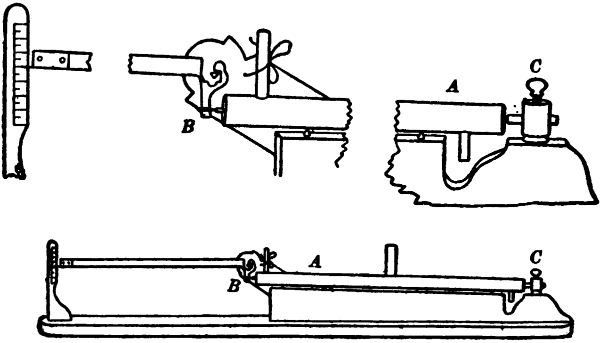

FIG. 174.

A tin steam jacket A contains a rod of the material of which the coefficient is to be determined. In order to magnify the motion, one end of the rod rests against the short arm of a lever B. The other end of the rod is prevented from moving by the screw C. When steam is passed into the jacket and the rod expands, it moves the short, arm of the lever and this in turn causes the long arm to move over the scale. Knowing the relative lengths of the lever arms, the actual motion of the rod may be found, and from this the coefficient.

The coefficient of expansion is very nearly the same at all temperatures between the temperature of the melting point of ice and the boiling point of water.

The table of coefficients follows:

Linear Expansion for 1° C.

Ice	0.002941	of its length.
Zinc	0.000029	"
Lead	0.000028	"
Tin	0.000022	"
Silver	0.000019	"
Copper	0.000017	"
Gold	0.000015	"
Iron	0.000012	"
Steel	0.000011	"
Platinum	0.000009	"
Glass	0.000009	"

A copper trolley wire, at the temperature of melting ice, is 100 feet in length: what will be its length at the temperature of boiling water? Here $100^\circ - 0^\circ = 100^\circ$, and $100^\circ \times 0.000017 = 0.0017$ feet expansion per foot, so that 100 feet will expand $100 \times 0.0017 = 0.17$ feet $= 2.04$ inches.

342. Examples of the Expansion of Solids.—When solid bodies expand or contract, they exert considerable force. The tires of wheels are made of such a size that, when cold, they will not go on the wheel; so they are heated until they are large enough to slip on easily, and when cold, they contract and fit very tightly to the wheel, holding its parts firmly together.

The rails of railways are laid with some little space between the ends, so as to leave room for expansion.

The snapping and crackling of a stove, when suddenly heated by building a fire, or when suddenly cooled by opening the stove door, is caused by the unequal expansion of the metal at different parts.

Thick glassware is sometimes broken when suddenly heated or cooled, on account of unequal expansion or contraction. When hot water is poured into a thick glass tumbler, the inside of the glass expanding before the outside becomes warm may cause the tumbler to break.

343. Expansion of Liquids.—Liquids expand when heated and contract when cooled proportionately more than do solids.

Water presents some curious phenomena in its expansion and contraction. When at the temperature of melting ice, 0° C. or 32° Fahr., water, if heated, contracts and grows denser, and this continues until the temperature of 39.2° Fahr. or 4° C. is reached; when heated above this point, however, it expands like most other substances. The temperature of 39.2° Fahr. or 4° C. is called the temperature of the *maximum or greatest density* of water. When water is at the temperature of its maximum density, it will expand, whether it be heated or cooled.

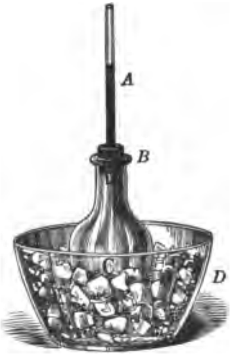

FIG. 175.

Experiment 76.—Fit a narrow glass tube *A*, Fig. 175, tightly in a cork *B*, and inserting the cork into the neck of a large bottle *C*, fill the bottle and tube with water to the point *A*. Place the bottle in a pan *D* and surround it with layers of broken ice and salt. As the water is cooled, the column of water in the tube will fall, thus proving that the water is contracting. But when the water is cooled to 39.2° Fahr., the column will cease falling, and will begin to rise, although the water is still growing colder.

The table below gives the expansion of different liquids at the temperature of 100° C.; the volume at 0° C. being unity. It will be seen from this table that of all the liquids named, mercury expands the least and alcohol the most.

Alcohol	1.11	Sulphuric acid	1.06
Linseed oil	1.08	Water	1.0466
Turpentine	1.07	Mercury	1.015

344. Peculiarities of the Freezing of Large Bodies of Water.—Let *A*, Fig. 176, be a deep lake of fresh water, in which the water is at the temperature of, say, 50° F. If the air grows cold, the water at the surface of the lake grows cold and sinks, because it contracts and becomes heavier than the rest of the water. When all the water in the lake reaches the temperature of 39.2° F., and is, therefore, as heavy as it can get by loss of heat, now, as the water near the surface continues to lose its heat, it grows lighter and remains at the surface until changed into ice. Since water conducts heat poorly, the water at the bottom remains unfrozen. Were it not for this peculiarity in its expansion, the water throughout the lake would continue to cool until the whole mass became solid, when not even a summer's heat would entirely melt it.

FIG. 176.

This peculiar action of water may be illustrated by Hope's experiment.

Experiment 77.—A glass cylinder is filled with water cooled to about 10° C. A mixture of ice and salt is placed in the pan encircling the cylinder. As the water in the cylinder cools it contracts, becomes more dense and sinks.

The lower thermometer, therefore, sinks until it reaches 4° C. Then, as the water cools, it expands and rises so that the upper thermometer now begins to fall, and continues to do so until 0° C. is reached, when the water freezes. If kept undisturbed, it is possible to cool the water below 0°, having it in a peculiar condition known as super-cooled. If now a crystal of ice is dropped into the water, it begins to freeze rapidly, and the temperature rises to 0°.

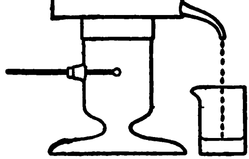

FIG. 177.—Hope's experiment.

345. Expansion of Gases.—At ordinary temperatures and pressures air expands about $\frac{1}{273}$ of its volume for each degree

Centigrade increase in temperature. At ordinary temperatures and pressures nearly all gases have the same coefficient of expansion as air.

When a given volume of gas at 0° C. is cooled one degree and the pressure kept constant, it contracts $\frac{1}{273}$ of its volume. The remaining volume is, therefore, $\frac{272}{273}$ of the original. If the volume is kept constant, the pressure is reduced $\frac{1}{273}$ for each degree Centigrade it is cooled. At $-273°$ there would, therefore, be no pressure. This temperature, $-273°$, is, therefore, called absolute zero. These facts about gases may also be expressed by Charles' law. *The volume of a gas is directly proportional to its absolute temperature.* By absolute temperature is meant temperature on a scale beginning at absolute zero, and whose degrees are the same as Centigrade degrees.

This law may be expressed by the proportion

$$V : V' :: T : T'. \quad (34)$$

Here V is the volume of the gas when the absolute temperature is T and V' is the volume of the gas when the absolute temperature is T'.

When the earth's atmosphere is heated, it expands; when cooled, it contracts. When any mass of air is heated, it expands, and, becoming lighter than the surrounding air, rises, while the cooler air on the sides blows in toward the place from which the heated air has risen. *Winds* are caused in this way.

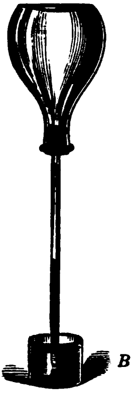

FIG. 178.

The draught in a chimney is caused by the air within the chimney being heated and rising, and the cooler air rushing in through the fire to take the place left by the rising air.

Experiment 78.—Place a narrow glass tube fitted airtight to a cork in the neck of a large bottle, A, of thin glass. Hold the bottle for a few minutes near a gas flame or a hot stove, and then quickly place it, as shown in Fig. 178, with the end of the tube dipping below the surface of some colored liquid in B. As the air in the bottle cools it contracts, and the pressure of the outside air causes a column of liquid to mount in the tube. If, however, the air in the bottle be again heated, as by holding the hand on it, the expansion of the air will drive the column of colored liquid down. This apparatus will, therefore, act like a thermometer; only the column of colored liquid falls when the air is warm, and rises when it is cold. It acts also somewhat like a barometer, since an increase in the pressure of the atmosphere will cause the column to rise, and a decrease in pressure will cause it to fall. Galileo made the first thermometer in this way about 1600

PROBLEMS

1. On a certain day the temperature of the air rose through 20° F. Through how many degrees Centigrade did it rise?

2. Find the temperature, on the Centigrade scale, corresponding to the following: 68° F., 120° F., 205° F., −80° F.

3. Find the temperature on the Fahrenheit scale corresponding to the following: 90° C., 4° C., 20° C., −10° C.

4. Express the freezing point of mercury (−38.5° C.) and its boiling point (357° C.) in Fahrenheit degrees.

5. Find algebraically the temperature at which the readings of a Fahrenheit and a Centigrade thermometer will agree.

6. An iron steam-pipe is 50 ft. long at 0°; what will be its length at 100° C.?

7. A copper rod, the length of which at 0° is 2 metres, is heated to 300°; what will its length now be? At what temperature will its length be 200.55 centimetres?

8. A certain quantity of gas measures 250 c.c. at 0° C.; what would be its volume at 65° C.?

9. A certain quantity of gas measures 90 c.c. at 0° C.; at what temperature will its volume become 120 c.c.?

10. A liter flask contains 1.293 gm. of air at 0° C.; how much will it contain at 100° C.?

11. At what temperature will the volume of a given mass of gas be exactly double of what it is at 25° C.?

12. Some hydrogen measured in the laboratory at 19° C. has the volume of 150 c.c. What would the volume be at 0° C.?

13. A vessel full of air at 0° C. is heated to 80° C., when 2 c.c. of the air (measured at 0°) are found to have escaped. How much air was in the vessel before heating?

CHAPTER XX

COMMUNICATION OF HEAT.—SURFACE ACTION OF BODIES

346. The Communication of Heat.—Heat may be communicated or transferred from one body to another in three ways:

(1) By conduction.
(2) By convection.
(3) By radiation.

Heat is communicated through solids by conduction, and through liquids and gases mainly by convection and radiation.

347. Conduction of Heat.—If one end of a short bar of iron, copper, or any other metal be placed in a fire, the other end will gradually become too hot to be held in the hand. The heat has been communicated from the fire to the rod and carried through the substance of the rod by *conduction*.

When the molecules at the heated end of the bar are set into more energetic motion by the heat of the fire, they gradually impart their increased motion to the molecules beyond them, and in this way heat is conducted through the bar. The rapidity of heat conduction from one end of a bar to the other is the same whether the bar be straight or bent. As a rule, heat is conducted better by solids than by liquids, and better by liquids than by gases.

348. Conductivity.—The rapidity with which heat is conducted varies greatly in different solids. If the ends of two rods of the same length and thickness, one of copper and the other of iron, be placed in a fire, under exactly similar conditions, the heat will be conducted through the copper rod much more rapidly than through the iron rod. Again, if a rod of glass be similarly placed in the same fire, it will be found to be a very bad conductor of heat.

Experiment 79.—Stick a number of marbles or buckshot, by means of wax, at equal distances apart, on two bars, *A*, of copper, and *B*, of iron, of the same length and thickness, as shown in Fig. 179. Expose one end of each bar to the same source of heat, as, for example, the flame of an alcohol lamp or Bunsen burner. It will be observed that the balls will fall sooner from the copper bar than from the iron, thus showing that the copper bar is the better conductor of heat.

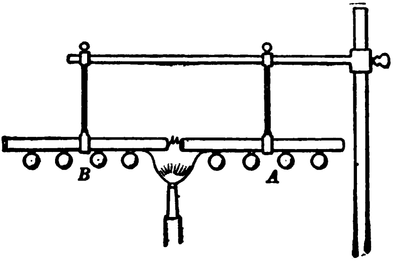

FIG. 179.

Experiment 80.—A Bunsen burner can be easily made as follows: Take a piece of tin in the shape of a rectangle, and cut out small pieces from one of its shorter ends, so that, when the tin is rolled in the form of a hollow tube, as shown at *B*, Fig. 180, there will be openings provided as at *A*. Fit the end *C* loosely over a gas-burner. Turn on the gas, and light it from above. If the burner has been properly made, the gas will burn with a faint bluish, but almost non-luminous flame, and will not soot articles heated in it. Air enters at the openings below, and burns the gas more thoroughly than an ordinary gas-burner. This flame is very hot; glass tubes held in it will soften and may be bent in any desired shape.

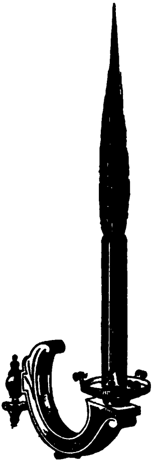

FIG. 180.

349. Applications of the Conductivity of Solids.—When a cold body is placed in contact with a hot body, the latter begins to lose heat to the former. If we wish to prevent this loss of heat by the hot body, we must surround it by some substance that conducts heat very poorly.

Ice is wrapped in blankets to keep it from melting, because the blankets have a low heat conductivity, and, therefore, prevent the heat from entering.

Thick woolen clothes are worn in winter to keep the heat of our bodies from escaping rapidly. Thin muslin or linen clothes are comfortable in summer, because they readily permit the heat of the body to escape.

Ice-houses are made with thick double walls, filled with shavings or sawdust, to keep heat from entering. For the same purpose, fire-proof safes have double or triple walls, filled with some poor conductor.

Very little of the heat of the interior of the earth reaches the surface, owing to the low conducting power of the materials forming the earth's crust.

350. Table of Conductivity.—The differences in heat conductivities are shown in the following table:

Table of Thermal Conductivities[1]

(Value expressed in C. G. S. units.)

Solids.		Liquids.		Gases.	
Aluminum	0.353	Alcohol	0.00042	Air	0.000568
Brass	0.226	Ether	0.00030	Carbon dioxid	0.000307
Carbon	0.0004	Mercury	0.0201	Hydrogen	0.000327
Copper	0.721	Petroleum	0.000355	Nitrogen	0.000524
Cork	0.0007	Water	0.0012	Oxygen	0.000563
Glass from	0.0005				
Glass to	0.0023				
Iron	0.164				
Lead	0.080				
Silver	1.096				

Here, as will be seen, silver and copper are relatively good conductors of heat, and lead and carbon are poor conductors. Alcohol has a lower conductivity than water. All gases are poor conductors.

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[1] From Smithsonian tables.

351. Conduction of Fluids.—Liquids and gases generally are very bad conductors of heat. When heated from below, they grow hot almost entirely by a process called *convection;* when heated from above, they conduct but very little heat downward, since convection cannot take place.

Experiment 81.—Insert the tube of the simple thermometer, described in Experiment 78, through a cork, and place the cork, as shown in Fig. 181, in the small end *A* of a funnel, the neck of which has been cut off. Fill the funnel with water, so as to cover the bulb *B* to the depth of about one-quarter of an inch. Pour some ether on the water, and set fire to it. So little heat will be conducted downward through the water, that the level of the column of colored water at *b* will scarcely fall.

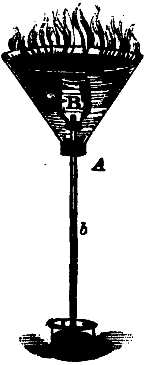


FIG. 181.

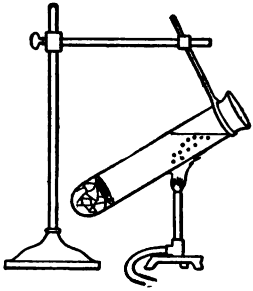


FIG. 182.

Experiment 82.—Place some small pieces of ice in the bottom of a large test-tube (Fig. 182), push in a piece of wire coiled in the form of a spiral, to prevent the ice from floating to the top, and fill the test-tube with water. Heat the water *above* the ice, and it will boil without melting the ice. Water is such a poor conductor that even when boiling hot the heat is not conducted to the ice.

352. Convection.—When a vessel containing a liquid is placed over a source of heat, the liquid touching the hot bottom of the vessel is heated, and, expanding, becomes lighter and rises, its place being filled by some of the cooler portions of the liquid falling. These in turn become heated, and are replaced by other portions, until at last the whole mass of the liquid is at the same temperature. Heat is transferred through gases in the same way.

This method of communicating heat is called *convection.* Liquids and gases are cooled in a similar manner.

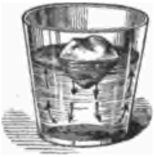


FIG. 183.

Experiment 83.—Place a lump of ice in a tumbler of tepid water. As the water which touches the ice is cooled it becomes heavier, and, sinking, pushes the warmer and lighter water up from below. By watching the water closely, these currents can be seen, especially if there are any little specks of dirt in the water. Their general direction is shown in Fig. 183, by the arrows.

During convection the warmer portions of the liquid or gas always rise and the cooler portions always fall.

Winds are huge convection currents in the air caused by the unequal heating of different portions of the surface of the earth. The constant oceanic currents are huge convection currents in the ocean, and are caused by differences of temperature between the water at the equator and at the poles.

The heating of houses by hot water is done by means of convection currents. This may be illustrated by the following experiment:

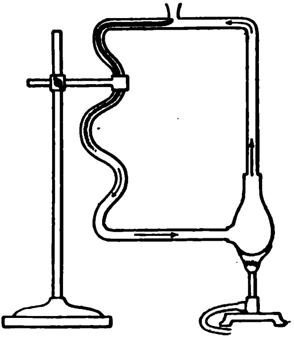


FIG. 184.

Experiment 84.—Fill the glass flask and tubes with water (Fig. 184) and heat the flask carefully. Convection currents are set up and may be readily shown by pouring some colored solution into the top of the funnel. The flask corresponds to the boiler in the cellar and the bent tubes to the radiators in the house. The warm water rises, gives out its heat, contracts, and flows back to the boiler.

353. Convection in Gases.—When a candle burns, the hot gases rise and are displaced by an inflowing stream of cold air, thus maintaining the necessary supply of oxygen. This circulation is easily shown as follows:

Experiment 85.—Mount two lamp chimneys over openings in the top of an otherwise closed tin box, as shown in Fig. 185. Place a candle under one of the chimneys and light it. The necessary oxygen is supplied by a stream of air entering by the other chimney, crossing the box, and rising with the hot gases of combustion. The course of the current may easily be shown by means of touch paper. (Filter-paper dipped in a solution of sodium or potassium nitrate and dried. When lighted, it burns with a great deal of smoke but no flame.)

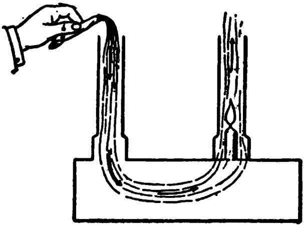


FIG. 185.

Ventilation can be maintained by means of convection currents. If the two chimneys in the above experiment represent shafts in a mine, it is easily seen how a bonfire at the foot of one shaft will cause a current of fresh air to cross the mine. Sometimes gas jets are burned in flues to increase the draught. The action of a chimney in carrying off the products of combustion from a stove is due to convection currents.

354. The Radiation of Heat.—*Radiant energy*, *i. e.*, the energy given off by the vibrating molecules of a heated body as a wave motion to the surrounding ether, may be either luminous or non-luminous. That is to say, a hot body will always radiate heat, but if its temperature is sufficiently high, some of the radiant energy may also be able to affect the eye as light.

If we stand at the same distance from a cylindrical stove, but on different sides, we shall find, if the stove is formed of the same material all around and the stove-door is shut, that the intensity of the heat thrown out or radiated is the same in all directions. It can be shown by experiment that a spherical vessel filled with hot water will radiate heat equally in all directions.

If a poker is moderately heated in a fire, it will, when withdrawn, radiate heat without giving out light. If, however, it is more strongly heated, it will glow when withdrawn from the fire, that is, it will throw out not only heat, but also light.

355. The Radiometer, an invention of Crookes, is an apparatus in which an easily rotated wheel, provided with vanes or arms surrounded by a gas in a high state of exhaustion is set into rapid rotation, when the opposite faces of the vanes are unequally heated by exposure to a source of light or heat.

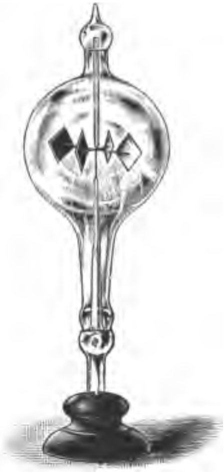


FIG. 186.

In order to insure this unequal heating of the opposite faces of the vanes, they are silvered on one side and covered on the other side with lamp-black.

The vanes are attached to a light vertical axis, as shown in Fig. 186. On exposure to light or heat the blackened surfaces absorb heat and become hot, while the silvered surfaces throw off the heat and remain relatively cold. The molecules of gas touching the heated surfaces are shot off with greater velocity from the lamp-blacked surfaces than from the silvered surfaces.

The reaction thus produced by the molecules flying from the lamp blacked surfaces causes a rotation of the vanes in a direction opposite to that in which the molecules fly off.

As the velocity of rotation of the vanes of the radiometer depends upon the amount of radiant energy received, this instrument can be used, as its name implies, to measure the amount of this energy.

356. Heat Radiated in Straight Lines.—If the medium through which radiant heat is passing be uniform throughout, the energy which is radiated from a heated body, like the light radiated from a luminous body, passes off from it in all directions in straight lines.

If a screen, through which radiant heat cannot pass, be interposed between a thermometer and a source of heat, the thermometer will show that it is no longer receiving heat from the source. If, however, the screen be removed, the thermometer will indicate a rise in temperature. On hot days it is cooler in the shade than in the sunshine, because all the radiation from the sun moves in straight lines.

When radiant heat passes from one medium to another medium of different density, it is bent out of its straight course like light, or is *refracted.* The common burning-glass owes its power of heating things placed at its focus to the fact that it is so shaped that both the luminous and non-luminous rays of heat from the sun are bent by refraction on passing through it, so that when they pass out, they nearly all collect at a single point or focus.

357. Intensity of Radiation.—The hotter a body is, the greater is the intensity of the radiation from it. As the molecules of a hot body have greater energy of motion than those of a cooler body, the energy of motion which the hot body communicates to the surrounding ether must be greater than that communicated by the cooler body.

The farther we go from a hot body, the less is the intensity of the heat we receive. The intensity of the heat radiated from any point of a hot body is inversely proportional to the square of the distance from that point. Generally, if we are twice as far from a hot body at one time as at another, the intensity of the radiant heat will be four times less. This decrease in the intensity of heat, with the increase of the distance, is similar to the decrease in the intensity of sound and light. See Par. 262.

358. Effects which Occur at the Surfaces of Bodies.—When the ether-waves emitted by a hot body strike against the surface of another body, they are either *thrown back* from it, *absorbed* by it, or *transmitted* through it. This is the same in the case of light. The light which reaches a surface is thrown back from that surface, *i. e.*, reflected or diffused; passes through it, as through glass or water; or is absorbed by it.

359. Reflection of Heat.—Since non-luminous heat differs only in frequency from light, it is to be expected that it obeys the same laws as light. In the case of reflection, heat-waves which strike a smooth surface are reflected from that surface at an angle equal to the angle of incidence.

Bodies vary greatly in their power of reflecting heat. Some bodies, like smoothly polished silver or gold, will reflect a large part of the heat which falls upon them, while others, like a rough, soot-covered surface, will reflect but little heat. As a rule, bright polished metallic surfaces are good reflectors of heat.

Experiment 86.—Hold a brightly polished piece of tin in front of an open fire, so as to reflect the light and heat. Notice that the spot where the patch of light reflected from the tin falls is warmer than the space around it, thus showing that the non-luminous heat of the fire is reflected as well as the light. Hold the tin so that the light of the fire is thrown into the face, and an increase of temperature will at once be felt.

360. Absorption and Radiation of Heat.—The ether-waves that are not reflected from the surface of the body on which they fall enter its substance, and are either *absorbed*, *i. e.*, give their to-and-fro motions to the molecules of the body, thereby making the body hot, or they pass through the body without heating it, merely giving their motion to the ether between the molecules.

If a body is a good absorber of heat, it must also be a good radiator or emitter of heat. Lamp-black is both a good absorber and a good radiator of heat.

If a body is a good reflector of heat, that is, if it throws off most of the ether-waves from its surface, it cannot, of course, take them in or be a good absorber.

Anything, therefore, which increases the reflecting power of a body must decrease both its absorptive and radiating power. Anything which increases the absorptive or radiating power of a body must decrease its reflecting power. Thus, smoothing and polishing diminish the absorptive and radiating powers, but increase the reflecting power. The opposite effects are produced by roughening or dulling a surface.

Bodies are continually radiating or losing their heat, no matter whether their temperature be the same as, or different from, the temperature of surrounding bodies, and thus tend to become lower in temperature, and to absorb the heat that falls on them from other bodies. When their temperature remains constant, it is because the quantity of heat they radiate and the quantity of heat they absorb are the same in any given time.

Experiment 87.—Fasten a short piece of copper rod to the middle of two pieces of tin plate (Fig. 187). Blacken the opposite side of one of these plates, but leave the other piece polished. Suspend the two plates so that they will hang parallel to each other, and fasten a marble by wax to the end of each rod. Place equi-distant between the two plates a hot ball. The marble attached to the blackened plate will drop off much the sooner, showing that it is the better absorber of heat.

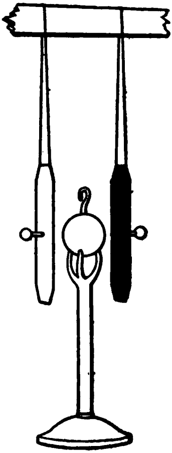


FIG. 187.

361. Applications of Absorptive, Emissive, and Reflecting Powers.—Coffee and tea are brought to the table in highly polished pots, which, being good reflectors of heat, are bad radiators. The contents of such pots will, therefore, keep warm for a greater length of time than if their outsides were rough and dull.

Meat roasters are so arranged that the radiant heat of the fire is reflected from the surfaces of brightly polished tin on the meat to be cooked.

If the outside of a stove be too brightly polished, much less of its heat will be radiated into the room than if the outside were rough and dull.

362. Selective Absorption and Selective Radiation.—The ability of a substance to throw off or radiate heat varies in a marked manner with the nature of the source of heat. Like a plate of red glass, which is transparent to red light, but opaque to blue light, a body may be transparent to much of the heat emitted by an incandescent platinum wire, although it is opaque to the heat emitted by a vessel filled with boiling water. We have seen that sound-waves, striking against the strings of a piano, may give part of their motion to the strings, provided the strings can vibrate at the same rate as the sound-waves which strike them; or, in other words, sound-waves excite sympathetic vibrations in the strings. The same is true with the ether-waves. If they strike against a body whose molecules are able to vibrate at the same rate as the ether waves, the heat is said to be absorbed, since the molecules are set into vibration. Otherwise, the ether-waves may simply pass through the body by setting the ether between the molecules into motion.

363. Diathermancy.—When the ether-waves pass through a body without heating it, that is, when they pass through a body without imparting their motion to its molecules, the body is said to be *diathermanous*, or transparent to heat. When it will not let the heat so pass through, it is said to be *athermanous*, or opaque to heat. In diathermanous bodies the ether-waves impart their motion to the ether between the molecules.

Clear rock salt is diathermanous to all kinds of heat. Dry air is diathermanous, but when it contains water-vapor, is less diathermanous. It is mainly to the vapor of water our atmosphere contains that it owes its power of absorbing a part of the sun's heat.

If our atmosphere contained no moisture, a larger proportion of the heat absorbed from the sun would be radiated at night into space. The moisture of the air makes it more athermanous, and, therefore, much more of the heat is retained.

The atmosphere of the moon is believed to be practically without moisture, and, therefore, the radiations must be very great, so that the cold is intense. A similar condition exists on the top of high mountains where, on account of the rarity of the atmosphere and the small amount of moisture present, the radiation is so great that at night the temperature becomes very low.

Diathermancy is independent of transparency. Thus alum freely allows light to pass through it, but stops non-luminous heat; while smoky quartz, which is almost opaque to light, allows heat to pass through it readily. A solution of iodine in bisulphide of carbon is opaque to light, but transparent to non-luminous heat.

Experiment 88.—Hold a piece of clear window-glass between the face and the open door of a fire, and observe that the face feels cooler when shielded by the glass. The glass is opaque or athermanous to the heat of the fire. Now hold the glass between the face and the sun, and no perceptible difference will be felt in the heat, whether the face be shielded by the glass or not; the glass, therefore, is diathermanous to the sun's heat radiation.

A gardener makes use of this principle in his "cold frame." During the day the sun's heat can penetrate the glass, as glass is diathermanous to heat from a body of such high temperature as that of the sun. But at night the earth inside the frame cannot lose its heat to the outside air, as the glass is athermanous to heat from a body of low temperature.

CHAPTER XXI

HEAT UNITS.—CHANGE OF STATE.—MECHANICAL EQUIVALENT OF HEAT

364. Heat Units.—The total quantity of molecular or heat energy present in any substance cannot be determined when only its temperature is known. A thermometer, plunged into a cup full of boiling water, would indicate the same temperature; viz., 100° C., as if plunged into a tub full of boiling water, although, manifestly, the quantity of heat energy present in the latter case is much greater than in the former. To determine the quantity of heat energy present in any case we must know:

(1) The kind of substance.

(2) The quantity of the substance; *i. e.*, its mass in pounds or grams.

(3) The temperature of the substance in degrees.

The quantity of heat energy is measured in units, called *heat units*. Two heat units are commonly employed: the *pound-degree Fahrenheit* or the British thermal unit, abbreviated to B. T. U., and the *gram-degree Centigrade*, or the small *calorie*; the former is the amount of heat required to raise the temperature of one pound of water 1° F. The latter is the amount of heat required to raise the temperature of one gram of water 1° C.

If, in the case alluded to above, the cup contained, say, one pound of water, and the tub, 1000 pounds, the quantity of heat present in the water in the tub would be 1000 times greater than the quantity of heat present in the water in the cup, provided both were at the same temperature.

365. Specific Heat.—Equal masses of different substances are not raised to the same temperature by equal quantities of heat. If we add the same amount of heat energy to a pound of mercury and to a pound of water, we shall find that if the water has been heated one degree, the mercury will have been heated thirty-three degrees. We conclude, therefore, that a given mass of water has thirty-three times the capacity for heat that an equal mass of mercury has.

Experiment 89.—Weigh into separate vessels 100 grams of lead shot and 100 grams of water. Immerse each in boiling water until they are at the same temperature. While they are heating, arrange a differential thermometer as shown in Fig. 188. Immerse each bulb in a beaker containing the same amount of water at the same temperature, say, 200 c.c. at 20°. The two bulbs of the thermometer being at the same temperature, the thermometer will read zero. Now pour the shot into one beaker and the hot water into the other. It will be very plainly evident that although the masses and the temperatures of the two substances were the same, the amount of heat in the water was very much greater than that in the lead. The water is, therefore, said to have a greater capacity for heat than the lead.

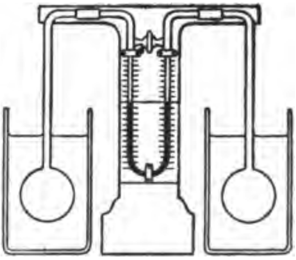


FIG. 188.

The *specific heat* of a body is the number of calories required to raise the temperature one gram of the substance one degree Centigrade. The specific heat of all common substances is less than that of water, which, by the above definition, is, of course, unity or *one*.

Experiment 90.—An experiment which illustrates the different specific heats of metals was designed by Tyndall. A number of small balls of various metals, as iron, lead, copper, tin, zinc, antimony, and bismuth, are provided each with a small hook. Heat them by suspending them in an oil bath nearly to the boiling point of the oil, say, 200° C. Then place them all at the same time on a sheet of wax. If they all had the same specific heat and were of equal mass, they would all hold equal amounts of heat, and would, therefore, melt their way through the wax at equal rates. It will be found, however, that the iron and copper will go through the wax quickly, while the bismuth will probably not melt through at all, the other metals being intermediate in their action. Evidently, although at the same temperature, they do not have the same amount of heat.

Specific Heats

Water	1.000	Iron, wrought	0.114
Alcohol	0.659	Nickel	0.109
Ice	0.504	Zinc	0.096
Steam	0.477	Brass	0.094
Marble	0.207	Copper	0.092
Phosphorus	0.202	Tin	0.056
Charcoal	0.242	Silver	0.056
Sulphur	0.163	Mercury	0.033
Steel	0.117	Platinum	0.032

366. The Method of Mixture is very commonly used in obtaining the specific heat of a substance. It consists essentially in mixing together known weights of the substance whose specific heat is to be obtained, and water, and noting the temperature of the mixture.

In such a case the calculation of the specific heat is made by the following method: Let m = the mass of water taken, t = the number of degrees of change of temperature, and s = specific heat of water. Let m', t', and s' be the corresponding values for the substance examined. The heat gained by the water is equal to that lost by the cooling body. Therefore, $m\,s\,t = m'\,s'\,t'$. Here s' is the only unknown, as s equals one.

$$\text{Therefore, } s' = \frac{m\,t}{m'\,t'}. \quad (35)$$

When any great degree of accuracy is desired, the heat absorbed by the calorimeter must be taken into account. That is, the "water equivalent" of the calorimeter must be added to

m, the mass of the water. The water equivalent is found by multiplying the weight of the calorimeter by its specific heat. A calculation of an actual experiment will make this clear.

Weight of calorimeter and water	210 gm.
Weight of calorimeter	110 gm.
Weight of water	100 gm.
Weight of lead shot	500 gm.
Temperature of the water	12° C.
Temperature of the shot	99° C.
Temperature of the mixture	22.8° C.

Then, $m = 100$ gm. $m' = 500$ gm. $t = 22.8 - 12 = 10.8°$ $t' = 99 - 22.8 = 76.2$; water equivalent $= 110 \times 0.095$ (sp. heat of calorimeter) $= 10.5$

$$s' = \frac{(m + \text{w. eq.})\, t}{m'\, t'} = \frac{(100 + 10.5)\, 10.8}{500 \times 76.2} = \frac{1193.40}{38100} = 0.0313 = \text{sp. ht. of lead.}$$

367. The Specific Heat of Water.—Water has a higher specific heat than almost any other common substance, that is, it takes in more heat when being warmed, and gives out more heat when being cooled, than any other common substance. Since about three-fourths of the earth's surface is covered with water, it is evident that the high specific heat of water must exert a great influence in preventing extremes of temperature, since water can absorb or emit considerable heat without much change in temperature.

368. Latent Heat.—When a gram of ice at 0° C. is melted, the water which comes from it is still ice cold, or at 0° C. All the heat which has been imparted to the ice to melt it has disappeared as heat; or, as it is called, has become *latent.* The gram of ice at 0° C. has been converted into a gram of water at 0° C. by the expenditure of a certain amount of heat energy. When this gram of water is frozen, all this latent heat becomes sensible.

When a gram of water is vaporized at 100° C., the steam which comes from it is still at 100° C., or is no hotter than the water. All the heat which has been given to the water to vaporize it has disappeared as heat; or, as in the case of melted ice, has become latent. The gram of water at 100° C. has become converted into a gram of steam at 100° C. by the expenditure of a certain amount of heat energy. When the steam is condensed, all this latent heat becomes sensible.

When a solid melts, or when a liquid vaporizes, heat energy disappears and ceases to exist as heat energy. This energy is expended in effecting the change of state or condition of the substance; *i. e.*, in doing internal work on the body. In other words, the kinetic molecular energy or heat is converted into potential molecular energy. Potential molecular heat energy was formerly called *latent heat*, and the word is, to some extent, still employed. The term is, however, misleading. Strictly speaking, such energy is not heat energy, though, like other forms of energy, it is capable of becoming changed into heat energy. In point of fact, when a fused substance solidifies, or a vapor condenses, the potential molecular energy appears as heat. The amount of heat energy required to fuse a given mass of a solid substance, or to vaporize a given mass of liquid substance, differs with different substances, but it is always the same with the same substance under the same circumstances.

369. Latent Heat of Fusion.—The heat required to melt a solid without changing its temperature is called latent heat of fusion. This constant for water may be determined by a method of mixture. Some dry ice is put into some warm water whose mass has been determined and whose temperature is known. The temperature of the water falls, and when all the ice is melted, is again recorded. The heat given out by the cooling water melted the ice and also warmed the resulting ice-water to the final temperature. The method of calculation is shown by the results of an experiment as follows:

Weight of calorimeter + water + ice	368.2
Weight of calorimeter + water	315.2
Weight of calorimeter	115.2
Weight of water	200.0 = A
Weight of ice	53.0 = B
Temperature of water	51°
Temperature of mixture	24°

Water equivalent of calorimeter = 115.2 × 0.095 (sp. heat of copper) = 10.9. Heat given out in cooling = $(A + \text{w. eq.})\, t = 210.9 \times 27 = 5694.3$. Of this B, (wt. of ice water) t' = heat used in warming the ice water = $53 \times 24 = 1272$. The difference 4422.3 = heat required to melt 53 grams of ice. Therefore, 83.4 units are required to melt one gram of ice. The correct value is 80. That is, to melt one gram of ice at 0° to water at the same temperature requires 80 lesser calories.

370. Laws of Fusion.—It can be shown experimentally that the following laws govern the fusion of bodies:

(1) Under the same pressure, every crystalline substance capable of fusion has a fixed temperature at which it begins to fuse.

(2) When any substance begins to fuse, the temperature remains constant until all the substance is fused.

Ice begins to fuse at the temperature of 0° C. If ice be placed in a vessel over a source of heat, a thermometer plunged in the water which comes from the melting ice will remain at the same temperature, 0° C., until all of the ice is melted.

371. Laws of Solidification.—Bodies which have been fused by heat, *solidify* when sufficiently cooled. Solidification is the reverse of liquefaction. The laws of solidification are similar to those of fusion; they are as follows:

(1) Under the same pressure, every substance solidifies at the same temperature as that at which it fuses.

(2) When the solidification has begun, the temperature remains constant until all the substance has solidified.

Water begins to freeze at 0° C., the temperature at which ice begins to melt. When a body of water which has been cooled to 0° C. begins to

freeze, the temperature of the water will remain at 0° C. until it is all frozen, no matter how intense the cold surrounding it.

Melting-points of Various Substances

	Degrees Fahr.	Degrees Cent.		Degrees Fahr.	Degrees Cent.
Iridium	3542	1950	Aluminum	1157	625
Platinum	3227	1775	Zinc	779	415
Iron	2822	1550	Lead	619	326
Steel	2462	1350	Tin	455	235
Gold	2156	1180	Ice	32	0
Cast iron	2012	1100	Mercury	—39	—39.5
Copper	1929	1054	Alcohol	—202	—130
Silver	1733	954	Oxygen	—296	—182

372. Effect of the Freezing of Water on the Temperature of the Air.—A large body of water cannot be cooled below the temperature of 0° C. until the entire mass has been changed into ice. During the change from water to ice a large quantity of energy in the water is liberated in the form of heat. Consequently, the freezing of large bodies of water tends to prevent the temperature of the surrounding air from falling below zero.

Both freezing and melting are gradual processes, because heat disappears when ice melts, and reappears when water freezes.

373. Freezing Mixtures.—Considerable heat disappears during the change of a solid into a liquid by solution. Hence, when solids are rapidly dissolved in a liquid, a marked cooling occurs. In some cases the liquid is warmed; here, however, a chemical combination occurs between the solid and the liquid, and more heat is produced than is absorbed during the solution.

Advantage is taken of the cooling produced by the solution of solids to obtain low temperatures artificially. *Freezing mixtures* consist of mixtures of different solids, or of different liquids and solids, which, when mixed, will dissolve, and so cause a reduction of temperature. By their use very low temperatures can be obtained.

A simple freezing mixture consists of one part of salt and two parts of ice or snow, spread in alternate layers. With this mixture a temperature as low as 5° F. can be obtained. Freezing mixtures are used in the preparation of ice-cream. The material to be frozen is put in a tin vessel, placed inside a larger vessel of wood. Salt and ice are packed in layers in the space between the two vessels. The salt causes the ice to melt rapidly, the heat necessary for the melting of the ice being taken from the cream, which is thus frozen. The outer vessel is made of some bad conductor of heat, such as wood, in order to prevent the ice obtaining heat from the air.

374. Increase of Volume during Solidification.—Some metals, such as mercury, contract on solidifying. It is for this reason that the freezing of the mercury in the bulb of a thermometer does not burst it. Other metals, like antimony, expand on solidifying; and hence fill the molds into which they have been poured, and so take sharp casts. Type-metal, an alloy consisting of three parts of lead and one of antimony, owes its power of taking sharp casts of the type to its expansion on solidification. Water expands with considerable force on freezing. Tubs filled with water are often burst during a cold night; even iron bomb-shells have been burst by filling them with water, and then exposing them to a freezing temperature.

The water, which is absorbed by porous rocks, or which runs into the crevices of those of more compact structure, may expand on freezing with sufficient force to break the rocks into fragments. In this manner water disintegrates or breaks down the rocks, and thus aids the rivers in carrying the mountains piecemeal toward the ocean.

375. Vaporization.—Nearly all liquids, when sufficiently heated, are *vaporized* or changed into vapors. When the vapor passes off from the surface only of the liquid, the liquid is said to *evaporate;* when the vapor is given off also throughout the mass, the liquid is said to *boil.* Some solids pass into a state of vapor without appearing first to become liquids; they are then said to be *sublimed.* Arsenic and camphor are examples.

376. Formation of Vapors in a Vacuum.—A volatile liquid, when placed in a vacuous or empty space, rapidly vaporizes.

A drop of any volatile liquid, if passed up into the empty space above the mercury of a barometer tube, will disappear and turn into vapor. At the same time the mercury column will be depressed, thus showing that the vapor exerts pressure. If more liquid be passed into the tube, it also will evaporate, and the column of mercury will be further depressed; but, after a certain amount of vapor has been formed, the amount depending on the temperature, the mercury column will remain stationary, and no more liquid will be evaporated. If more liquid be passed into the tube, it will simply float on top of the mercury. The vapor in the tube is then at its *maximum* or greatest pressure, and the space it occupies is said to be *saturated* with vapor. If, now, the tube be heated, more of the liquid will evaporate, and the mercury will be further depressed.

377. Circumstances Influencing Evaporation.—The rapidity with which a liquid evaporates, depends:

(1) On the extent of the surface exposed; because evaporation takes place at the surface.

(2) On the quantity of the same vapor already present in the air; because, when the air is saturated, no more of the liquid can evaporate.

(3) On the removal of the air; because evaporation ceases when the air over the liquid is saturated; if, however, fresh air is brought to the surface, more liquid evaporates.

(4) On the temperature; because the pressure of water vapor increases with the temperature.

(5) On the pressure on the surface; because the greater the pressure, the less the evaporation. In a vaccum all vaporizable liquids rapidly vaporize.

In drying clothes, they are spread out on lines rather than rolled up. It is known that clothes dry more rapidly on a warm day when the wind blows, than on a cold day when the air is still.

A pint of water poured into a narrow-necked bottle will evaporate less rapidly than a pint of water poured into a plate, and this in its turn will evaporate less rapidly than a pint of water sprinkled upon the surface of a sheet.

378. Laws of the Boiling of Liquids.—The laws for the boiling of liquids are similar to those for the fusion of solids. They may be expressed as follows:

(1) *The pressure remaining the same, there is for every liquid a certain temperature at which it boils.*

(2) *When a liquid has been heated to the boiling point, the temperature remains the same until all the liquid has been vaporized.* All the heat a liquid receives after it has once reached its boiling point is rendered latent in converting the liquid into vapor.

Boiling Points

	Degrees Cent.
Ether	35.0
Alcohol	78.3
Benzene	80.5
Mercury	358.0

379. Influence of Pressure on the Boiling Point.—Before a liquid exposed to the air can boil, its vapor must possess a pressure sufficient to enable it to overcome the pressure of the air. *Hence, the pressure of the vapor escaping from a boiling liquid is equal to the pressure of the atmosphere.* If, therefore, the pressure on a liquid is increased, the pressure of its vapor must be increased before the liquid can boil; that is, the temperature of the liquid must be raised. The boiling point of a liquid is, therefore, defined as that temperature at which its vapor pressure is equal to that of the atmosphere.

Experiment 91.—To prove that the boiling point of water is that temperature at which its vapor pressure is equal to that of the atmosphere. Fill a barometer tube with mercury, invert in a dish of mercury, and pass a little water up into the tube. Surround the tube by an outer glass tube and use it as a steam jacket (Fig. 189). When the steam is passed in, the mercury

is gradually depressed until finally the level inside and out is the same. The pressure now is evidently the same inside and out. But the pressure inside is merely that of the vapor of boiling water, while that outside is that of the atmosphere. Therefore, at the boiling point the two pressures are equal.

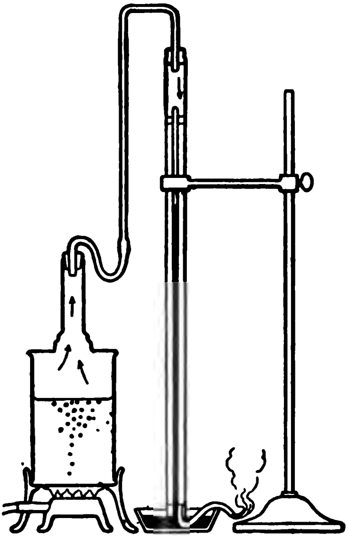


FIG. 189.

A liquid can never be raised above the temperature of its boiling-point while its vapor is allowed to escape into the air. If the vapor be confined, the pressure on the surface is increased, and the temperature can be increased to any extent, provided the vessel is sufficiently strong. To extract glue from bones, they are heated at very high temperatures, in water placed in closed vessels provided with safety-valves for the escape of the steam should the pressure become too great.

That the temperature of a vessel does not rise above the boiling point may be shown by the following curious experiment:

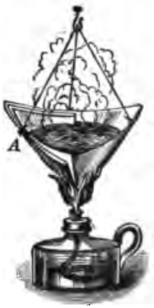


FIG. 190.

Experiment 92.—***To boil water in a paper bag.*** **Take a square piece of paper and fold it so as to form a conical bag *A*, as shown in Fig. 190. Suspend the bag by strings, and pouring water into it, allow the flame of an alcohol-lamp, or Bunsen burner, to fall on the bag, being careful to prevent the flame from touching the paper in any place where there is no water. The water can now be heated until it boils, without the paper being burned, because the paper cannot be heated much more than 100° C., and this is not sufficient to burn it.**

Experiment 93.—That a diminished pressure lowers the boiling point may be shown by an experiment sometimes called the *culinary paradox.* Water is boiled in a round-bottomed glass flask *A*, Fig. 191, and after a few minutes of vigorous boiling, so as to permit the steam formed to drive all the air out of the flask, the source of heat is removed, and the neck is closed by a rubber stopper. The vessel is now inverted with its neck below a water-surface, *C*, in order to prevent the entrance of air. For a few moments the water will continue to boil; but the increased pressure on the surface, produced by the confined vapor, soon *raises the boiling point and stops the boiling.* Now let some cold water fall on the bottom of the flask, as shown. The vapor will then be condensed, and the pressure being diminished, the liquid bursts into vigorous boiling. Pour hot water on the flask and it will again stop boiling.

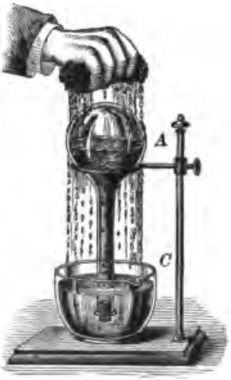


FIG. 191.

380. Influence of Dissolved Substances on the Boiling Point.

—Solids dissolved in a liquid increase the temperature of its

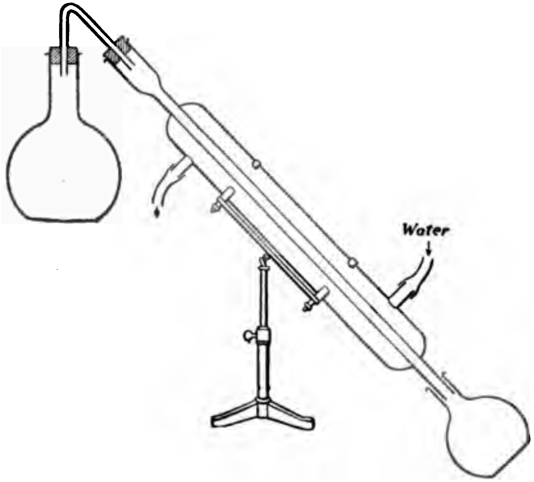


FIG. 192.—Condenser.

boiling point. Thus water, containing as much salt as it will hold, boils at the ordinary pressure at 109° C.

Distillation is a process by which a liquid can be separated from a solid dissolved in it. The vapor which escapes from a liquid containing a solid in solution does not carry the solid with it. If, therefore, we boil the solution and condense the vapor as it escapes, we separate the liquid from the solid. The process of distillation is frequently carried out by means of the apparatus shown in Fig. 192. The vapor passes into a tube which is cooled by a stream of cold water running in the outer jacket. The vapor from boiling ocean water, when condensed, yields water entirely free from salt. Rain is due to condensation water evaporated mainly from the ocean.

381. Heat of Vaporization.—The amount of heat expended during the change of one gram of water at 100° C. into steam at 100° C., is sufficient to raise the temperature of about 537 times as much water 1° C.; or is equal to 537 calories.

When vapor loses heat and condenses, the latent heat again appears as sensible heat. Thus, large buildings are frequently warmed in winter by the exhaust steam from a steam engine. The steam is passed through pipes, and, as it condenses in these pipes, it gives out its latent heat.

382. Latent Heat of Vaporization.—The heat required to change a liquid, at its boiling temperature, into vapor without causing change of temperature is called latent heat of vaporization. This may be determined for water by the method of mixture. Into a weighed amount of cold water, whose temperature is known, is passed dry steam until there has been a considerable change of temperature, say, 30°. The heat which warmed the cold water came from two sources. Part came from that given out by the steam in condensing to hot water. The rest came from the hot water cooling to the final temperature. The method of calculation may be seen from the following experiment.

Weight of calorimeter, water, and steam	428.7 gm.
Weight of calorimeter and water	413.6
Weight of calorimeter	113.6
Weight of steam condensed	15.1 (*A*)
Weight of water	300.0 (*B*)
Final temperature	36° C.
Temperature at first	7° C.
Change of temperature	29° C.

The weight of water (*B*) plus the water equivalent of the calorimeter, multiplied by the rise in temperature, gives the heat received $(300 + (113.6 \times 0.1))\ 29 = 9029.44$. Of this heat, 966.4 units came from the cooling of 15.1 grams of hot water from 100° to 36°. Deducting this 966.4 from the total heat received, there is left 8063.04 calories due to the condensation of 15.1 grams of steam. Therefore, the heat given out by one gram of steam in condensing is 534 calories. The correct value is 537 calories. It will be noticed that no attempt has been made to determine the heat required to convert 1 gram of water at 100° C. into steam, but rather the reverse, to find how much heat is given out by one gram of steam changing to hot water.

383. Reduction of Temperature Caused by Evaporation.—We are cooled by fanning, because the air, thus brought into contact with the skin, causes a rapid evaporation of the moisture of the skin, and thus lowers the temperature.

If water be placed in a vacuous space, and the vapor which escapes from it is removed as rapidly as it is formed, the water will be frozen by its own evaporation. *Ice machines* can be constructed on this principle. The water must take in heat in order to evaporate, and this heat is taken from the rest of the water, which is thus frozen.

When water evaporates at temperatures below the boiling point, a still greater amount of heat disappears. During the change of water into vapor by the heat of the sun, 537 calories per gram of water, or water vapor, are absorbed. This heat again becomes sensible as the water condenses. Since much of this condensation takes place in cold countries, we can see that such countries must be made warmer by means of the rain or snow which falls in them.

384. Mechanical Equivalent of Heat.—Energy can never be annihilated. When it disappears in one form it invariably reappears in some other form. Heat is the most usual form into which mechanical motion can be changed; for, since heat is the vibration of the molecules of bodies, we can easily change mechanical motion into heat. The fact that heat is a form of energy was first proved by Benjamin Thomson, an American, now generally known as Count Rumford. (See Par. 334.)

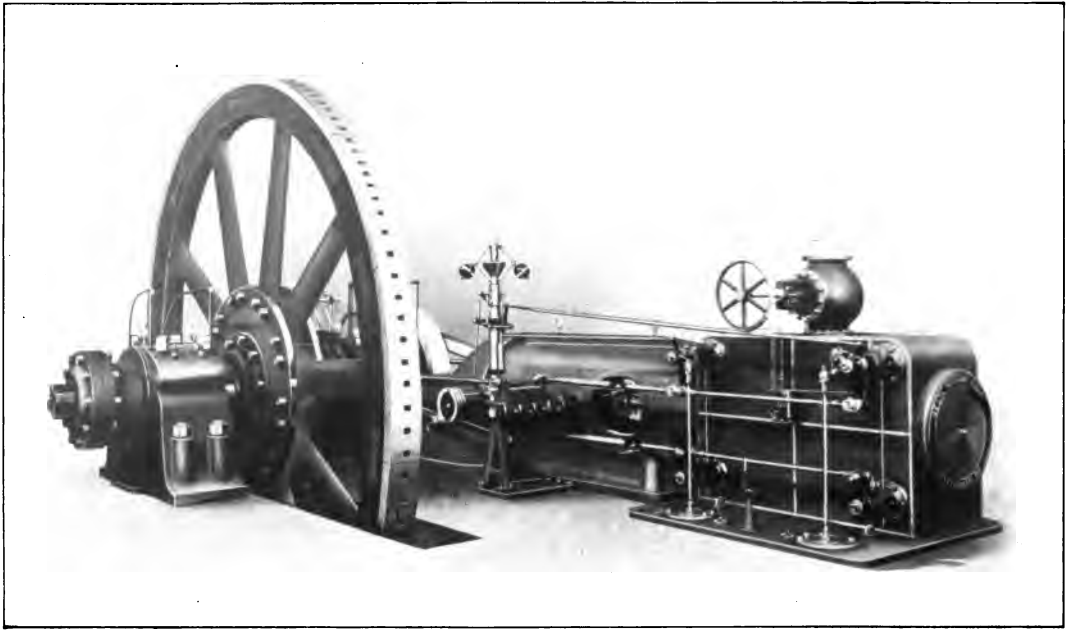
As the result of many accurate experiments we know the amount of mechanical energy necessary to produce a given quantity of heat.

The work necessary to produce sufficient heat to raise the temperature of one pound of water 1° F. is equal to that expended by a weight of 778 lbs., falling through the space of one foot. Conversely, one pound of water, cooling through 1° F., gives out a quantity of heat which, could it be utilized, would be capable of exerting mechanical energy sufficient to raise 778 lbs. through the space of one foot. These figures were first determined by an Englishman named Joule, and are called *Joule's equivalent.*

Joule determined the mechanical equivalent of heat by allowing a known weight to fall through a measured distance, and causing this to rotate a paddle in a vessel of water. The resistance caused heat, which was measured by the change in temperature of a known weight of water. These experiments were repeated in 1880 by Rowland of Johns Hopkins University, who obtained more accurate results than Joule. His results give 427 gram meters or 4.19×10^7 ergs as the value for the mechanical equivalent of heat, that is, the work equivalent to one lesser calorie.

385. The Steam Engine.—A method very commonly adopted for the change of heat into mechanical work is by means of the *steam engine* (Fig. 193).

The heat is employed to change water into steam. The water is placed in a suitable vessel, made of steel, called the *boiler;* the construction of which varies with the character of the steam engine with which it is to be used. The steam passes from the boiler through a pipe leading to a box called the *steam*



A Horizontal Steam-engine.

chest, through which, by a contrivance called the *slide valve*, it is admitted alternately to opposite ends of a cylinder *D*, in which is a freely moving piston.

By the pressure which the steam exerts the piston is moved backward and forward from one end of the cylinder to the other. The motion of the piston is communicated by means of the piston rod *E*, to a connecting-rod *F*, by which the motion is carried to a large heavy wheel *I*, called the *fly-wheel*. The alternating motion of the piston rod is converted into a steady rotary motion by means of a crank *J*. In this manner the backward and forward motion of the piston produces a continuous rotary motion of the fly-wheel. *Pulleys* are usually attached to the axis of the fly-wheel, from which, by means of *belting* and *shafting*, the motion is carried to the machinery to be moved.

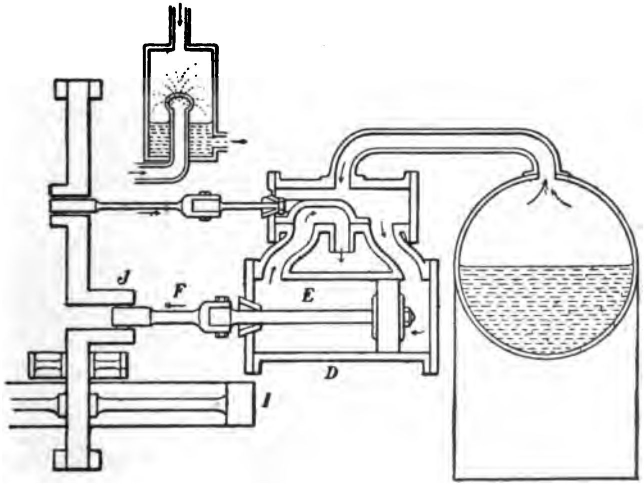


FIG. 193.

By means of the slide-valve the steam in the steam-chest is alternately cut off from one end of the cylinder and admitted to the other end, and at the same time an opening is provided through which the steam may escape from that end of the cylinder from which the steam has been cut off. In the *condensing steam-engine* this steam passes through a pipe into a chamber called the *condenser.* In this chamber a jet of cold water is allowed to play. By this means the steam, which passes from the steam cylinder into the condenser, is condensed, thereby lowering the pressure on that side of the piston from which the steam has just been cut off. A pump, called the *air-pump*, removes the water from the condenser. The slide-valve is moved by a rod, which is actuated by an *eccentric rod.*

In the *non-condensing engine* the steam escapes at once into the air, after it has moved the piston to either end of the cylinder. The puffs of steam which escape from such engines denote the speed with which the piston is being driven backward and forward.

When the piston is at the farthest part of its stroke; that is, when it is at either end of the cylinder, the crank J and the connecting-rod F are in the same straight line. These two positions are called the *dead points* of the engine. The fly-wheel by its inertia continues to move and carries the crank past these points.

386. Thermal Value of Coal.—

Steam engines and boilers form one of the mechanisms by which, at the present time, mechanical power is generated from coal.

One pound of pure carbon when burned produces about 14,000 British thermal units of heat. Anthracite is about 95 per cent. carbon, so that the heat produced from the burning of the carbon of a pound of hard coal is about 13,300 B. T. U. As each B. T. U. is equivalent to 778 foot-pounds of work, the heat liberated in burning one pound of anthracite is, therefore, equivalent to 10,347,400 foot-pounds.

This same statement may be expressed in terms of the C. G. S. system and Centigrade degrees as follows: One gram of pure carbon when burned produces about 8000 small calories of heat. Anthracite is about 95 per cent. carbon, so that the heat produced from the burning of the carbon of a gram of hard coal is about 7600 calories. As each calorie is equivalent to 4.2×10^7 ergs of work the heat liberated in burning one gram of anthracite is, therefore, equivalent to 3192×10^8 ergs.

Considering the heat which is liberated by the combustion of coal in air, the amount of power which can be developed by the best engines and boilers is comparatively small. The best steam engines and boilers fail to utilize at least 85 per cent., and can develop only about 15 per cent. of the power equivalent to the heat produced by the coal they burn.

387. The Gas-engine.—Another method by which the energy of a combustible substance may be used to do mechanical work is by means of the *gas-engine*. There are many kinds of these which use various forms of fuel, such as natural gas, coal-gas, or carbureted air.

In the steam-engine the fuel is burned under the boiler, thus heating water and producing steam. The losses by this method are so great that only a small proportion of the heat value of the fuel is used to do useful work. In the gas-engine the combustion takes place inside the engine itself, so that the losses are less and the efficiency of the engine greater. A form in common use is the *four-cycle* type, so called because the complete operation consists of four periods or cycles, while the fly-wheel of the engine makes two revolutions.

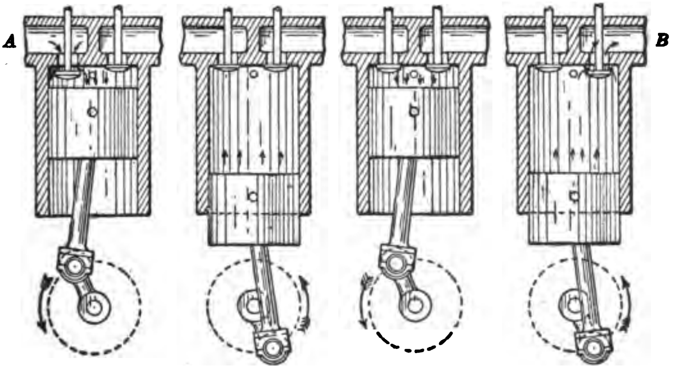


FIG. 194.—The gas-engine.

An inspection of Fig. 194 will show the operation of the engine. During the first period, while the piston is moving down, an explosive mixture of air and gas is sucked into the cylinder through the valve A. During the second period, while the piston is going up, the gaseous mixture is strongly compressed. By means of a flame or a spark the mixture is now exploded and the piston driven violently down, forming the third period. During the fourth period the piston goes up and drives out the waste gases through the valve B. Both valves A and B are opened and closed automatically at the proper time.

As the third cycle is the only one in which the piston is acted upon by the gaseous pressure, a heavy fly-wheel is needed to store up the energy and to keep the engine going during the other three cycles.

As great heat is developed during the explosion, the cylinder must be cooled by some means. This is usually done by a current of water, but in some cases is accomplished by air currents.

PROBLEMS

1. A flask holds 500 c.c. of water at its temperature of maximum density. How much heat must be given to the water before it just begins to boil?

2. How many calories are required to raise the temperature of 200 grams of copper from 15° C. to 250° C.?

3. Find the specific heat of a substance 124 grams of which at 75° C. when immersed in 240 grams of water at 11° C. gave a resulting temperature of 17° C.

4. A platinum ball weighing 80 grams was heated in a furnace and then dropped into 400 grams of water at 15° C. The temperature of the water rose to 20° C. What was the temperature of the furnace?

5. 105 grams of copper at 98.5 ° C. are mixed with 90 grams of water at 10.3° C. The temperature after mixing becomes 19.2° C. What is the specific heat of the copper?

6. What will be the result of mixing 10 pounds of snow at 32° F. with 4 pounds of water at 140° F.?

7. How much ice at 0° C. will be melted by 700 grams of boiling water?

8. 300 grams of melting ice are mixed with 700 grams of boiling water and the resulting temperature is 46° C. What is the latent heat of fusion?

9. How many grams of ice must be dissolved in 2 litres of water at 25° C. to reduce its temperature to 10° C.?

10. What will be the resulting temperature if 10 grams of ice at 0° C. are put into 200 grams of water at 10° C.?

11. How many calories will be required to convert 100 grams of water at 10° C. into steam at 100° C.?

12. If 50 grams of ice are melted and then completely vaporized, how many calories will be required?

13. How many pounds of steam at 100° C. will just melt 100 pounds of ice at 0° C.?

14. Find the latent heat of vaporization of water from the following data: Into 450 grams of water at 6° C. is passed 38 grams of steam at 100° C., the temperature of the mixture rising to 55° C.

15. To how many foot-pounds of energy are 8 calories of heat equivalent?

16. How many calories will be needed to convert 10 grams of ice at —10° C. into steam at 110° C.?

17. Water boils in the city of Mexico at 92.3° C. What is the height above sea level? (A change of elevation of 295 m. makes a difference of 1° C. in the boiling point.)

18. A mass of 400 grams moving with a velocity of 50 m. per second is stopped. If all the energy is converted into heat, how much will it produce?

19. Through what distance must 5 kgm. of water fall to raise the temperature 5° C. if all the energy goes to heating the water?

PART VI

MAGNETISM AND ELECTRICITY

CHAPTER XXII

MAGNETISM

388. Magnets.—A variety of iron ore known as magnetite has the power of attracting small pieces of iron. The name magnetite probably comes from the province of Magnesia in Asia Minor, where large bodies of this ore were found. When placed in iron filings a piece of magnetite attracts them and they group themselves in tufts at the corners of the piece of ore. Such a piece of ore is called a natural magnet. Only very few substances are attracted by a magnet. Iron shows this property in a great degree, while nickel and cobalt show it in a much less amount. Other substances, if they are magnetic at all, show the property in a very slight amount.

Experiment 94.—Rub a steel sewing needle on a piece of magnetite so that the part from the middle to the eye is rubbed on one end of the piece and the other end of the needle to the point is rubbed on the other end of the piece. It is best to draw the needle always in the same direction over the ore. The needle will now be found to have the power of picking up iron filings, just as the magnetite has.

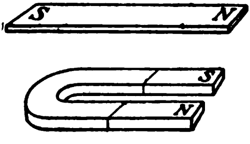


FIG. 195.

Any piece of iron or steel which has acquired magnetic properties by contact with magnetite or by any other method may be called an artificial magnet. We will see later that this property may be imparted more readily by the use of an electric current. Artificial magnets are usually either bar magnets or else horseshoe magnets (Fig. 195).

A piece of hard steel may retain its magnetism indefinitely. It is, therefore, called a *permanent magnet.* A piece of soft iron, on the contrary, retains very little of its magnetism after it has been removed from the magnetizing influence, and is, therefore, called a temporary magnet.

389. Polarity.—

Experiment 95.—Put a bar magnet on top of some small tacks spread out on a table, and then lift it up. The tacks will be found to cling to the magnet, but in unequal numbers at different parts.

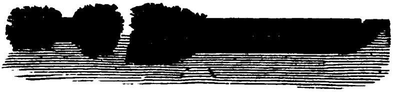


FIG. 196.

The places near the ends of the magnet where most of the tacks collect are called the *poles* of the magnet. If placed in iron filings, the same effect may be shown in a very interesting way.

Experiment 96.—Suspend a bar magnet by means of a wire stirrup hanging from a thread. After swinging for a while, it will finally come to rest, pointing toward the north. Displace it gently and it will come back to the same position. Mark the end pointing north, *N*, and the other end, *S*.

The pole which points toward the north is best called the north-seeking pole, and the other the south-seeking pole. They are also called North or positive (plus), and South or negative (minus).

390. Laws of Magnets.—A magnet mounted on a pivot so that it may move freely is called a magnetic needle (Fig. 197). Such a needle may be used to prove the laws of magnetic action.

Experiment 97.—Let the needle come to rest and mark the north-seeking pole. Now bring the *N* pole of a bar magnet near the *N* pole of the needle. The needle will move so that its *N* pole is repelled. Reverse the poles of the bar magnet, and the *N* pole of the needle will be attracted. In the same way the *S* pole of the bar magnet will repel the *S* pole of the needle but will attract the *N* pole of the needle.

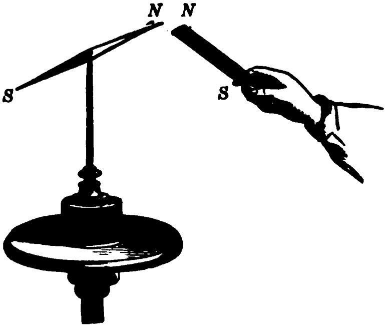


FIG. 197.

This shows the general law of magnets: Like poles repel each other; unlike poles attract each other.

Experiment 98.—Bring a bar magnet close to a magnetic needle and it will be violently disturbed. Separate the two, and the action of the needle becomes much less. Evidently the effect of one magnet upon another varies with their distance apart.

Coulomb found that the force exerted between two poles was proportional to the product of the strength of the poles, and inversely proportional to the square of the distance between the poles:

$$F = \pm \frac{m\,m'}{d^2}. \qquad (36)$$

If both poles are of the same kind, the sign is plus and the force is a repulsion. If the poles are of unlike kind, the sign is minus, and the force is an attraction. Unit pole may then be defined as such that when two unit poles are placed at a distance apart of one centimetre, they repel each other with a force of one dyne.

391. Magnetic Induction.—

Experiment 99.—Suspend an iron nail from one end of a magnet. The nail will be found to have acquired magnetic properties and can itself act like a magnet, and can attract another nail. If the magnet is strong enough, it can hold up a string of tacks and nails in this way. If, however, the first nail is removed, all the other nails and tacks will fall.

The nail became a magnet when it was in contact with the bar magnet, but lost the magnetism when removed. In the same way if a nail is brought near a magnet and not allowed to touch it, it will acquire magnetic properties. Magnetism produced in this way is called induced magnetism, and the process is called magnetic induction.

If the polarity of the nail is tested by a needle while near the bar magnet, the near pole will be found to be of the opposite sign, and the far pole of the same sign as that of the inducing pole (Fig. 198).

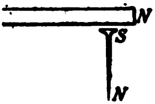


FIG. 198.

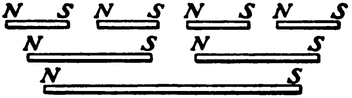


FIG. 199.

392. Molecular Theory of Magnetism.—

Experiment 100.—Magnetize a large steel needle and put it in iron filings. Poles will be shown near the two ends, but no filings will adhere in the middle. Now cut the needle in the middle and the broken ends will each show polarity. This may again be repeated with each half with the same result (Fig. 199).

Experiment 101.—Count how many tacks a bar magnet can pick up, then jar it roughly and it will be found to have lost some of its magnetism, as shown by the fact that it will not pick up as many tacks. If a magnetized needle is heated red-hot, it will be found to have lost its magnetism, so that it will no longer have any power of repulsion for a magnetic needle.

All these facts about magnetism, and many more besides, may be explained by the theory that the magnetism has a connection with the molecules of the iron. This is best illustrated by Ewing's model, as shown in Figs. 200 and 201. This consists of a number of small compass needles mounted between plates of glass. The small needles are quite close to each other, but free to swing around without touching. The whole is surrounded by several turns of insulated wire with binding posts attached.

When an image of this is projected on the screen, at first the little magnets are not arranged in a definite order. They are either haphazard or form, as it were, chains. If the circuit is closed and an electric current is sent around the field, the magnets swing into position and become parallel.

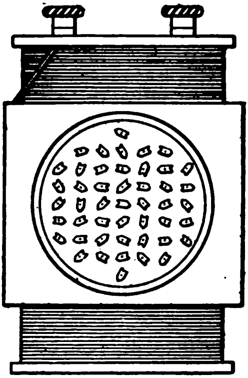


FIG. 200.—Before magnetization.

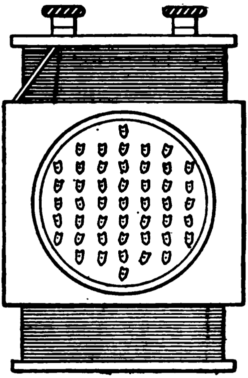


FIG. 201.—After magnetization.

The suggestion seems very reasonable that something like this condition of things holds in a piece of iron. In the unmagnetized condition the molecular magnets are haphazard, but under the inductive action of a magnet or of a current they are turned until they are parallel, when polarity is shown. When jarred away from this influence, they again swing out of their parallel positions. The fact that there is a limit to the magnetism which may be given to a piece of iron is then probably due to the fact that all the molecular magnets have become parallel. The magnet is then said to be *saturated*. If the material is easily magnetized, like soft iron, it is said to have high *permeability*, and the molecular magnets may be supposed to be easily moved. If the material holds its magnetism strongly, like steel, it is said to have high *retentivity*, and the molecules apparently are not easily moved out of their positions when they have been made parallel.

393. Line of Force.—If a small magnetic needle is placed close to one pole of a bar magnet, it will finally come to rest pointing in a certain direction. If an isolated pole without inertia could be obtained and it should be placed beside the like pole of a magnet, it would be repelled along a path which would finally lead in to the other end of the magnet. These lines, parallel to which the magnetic needle sets itself, or along which a single pole would tend to move, are called *lines of force*. Their direction is the same in which a north pole would tend to move when placed beside a like pole. If one stands with his back to the north pole of a magnet, he is looking in the same direction as the line of force coming from that pole.

394. Magnetic Field.—The region around the magnet in which space there are lines of force, as shown by the action of the magnetic needle or of iron filings, is known as a *magnetic field.* A picture of a magnetic field may be traced by moving a small magnetic compass so that the needle always moves in the direction in which it points (Fig. 202).

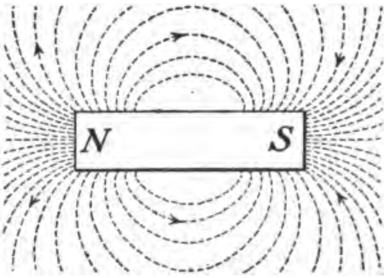


FIG. 202.

The field around a magnet is easily mapped by placing it under a piece of glass or cardboard and sifting iron filings on the plate. These arrange themselves so that they ar

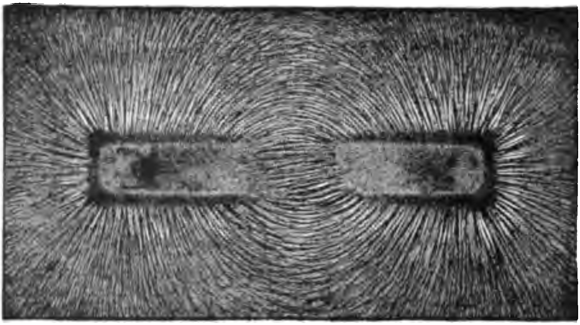


FIG. 203.

parallel to the lines of force. Permanent records may be made by using a photographic plate or sensitive paper and

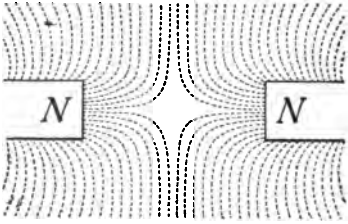


FIG. 204.

exposing it to the light after the field has been outlined by the filings. The plate or paper is then developed as usual. Fig. 203 shows the field around a bar magnet obtained in this way.

If like poles are placed near each other, the lines of force repel each other, as is shown by the picture in Fig. 204. If unlike poles are placed near each other, the lines of force pass directly from one pole to the other, as shown by the picture in Fig. 205.

395. Magnetic Flux.—A magnet may be regarded as any body through which magnetic flux is passing. Magnetic flux is invisible, but it is generally regarded that it comes out of a

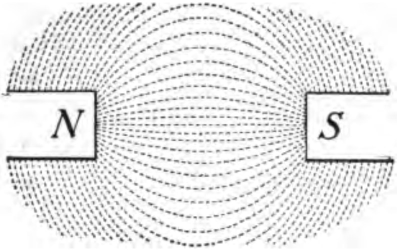


FIG. 205.

magnet at its north pole, and after passing through the space or region outside, reënters it at its south pole.

Magnetic attraction and repulsion can be explained as a result of magnetic flux or *magnetic streamings*, as they are also called. If a magnetic needle is brought into the neighborhood of the north pole of a bar magnet, under the influence of the streamings of the magnet and those of the needle, the needle is turned around or moved until its south pole points toward the north pole of the bar magnet, and it only comes to rest when the streamings of the magnet and of the needle are similarly directed.

In magnetic induction, magnetism is produced by the passage of magnetic flux through a substance. If a piece of soft iron is brought near the north pole of a magnet, the end nearest the north pole acquires south polarity, and the end furthest from it, north polarity. This is because flux from the magnet enters the piece of soft iron at the end nearest the magnet, and leaves it at the end furthest therefrom.

396. Permeability.—If a piece of soft iron be placed between the poles of a horseshoe magnet (Fig. 206), it will be found to alter the field. The lines of force or magnetic flux appear to prefer passing through the iron to passing through the air

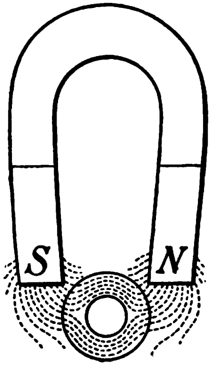


FIG. 206.

The iron is, therefore, said to have greater permeability than the air. It is on account of this fact that iron is used for magnetic screens. Valuable watches are often provided with soft iron shields: the magnetic flux passes into the iron instead of across it to the watch.

397. Terrestrial Magnetism—The Earth a Magnet.—The earth acts as if it were a huge magnet, thus affecting the position of the compass needle in a similar way to that in which a bar magnet affects it when near it. Since opposite poles attract, the ends of the needle which point toward the north must be of opposite polarity to that pole of the earth to which it points. It is, therefore, best to speak of the north-seeking and south-seeking poles of a magnet, or briefly, the *N* and *S* poles. This method of naming avoids the difficulty of naming that pole of the compass North which points to the north pole of the earth.

398. Inclination.—**Experiment 102.**—Place a large bar magnet on a table and on this place a magnetic needle mounted on a horizontal axis. As this is moved along the bar magnet it will assume different positions. Near one end it will be vertical, but in the middle it will be horizontal, and at the other end it will be vertical, but with the poles reversed from the first position. In each case it will be found that unlike poles of the two magnets attract each other.

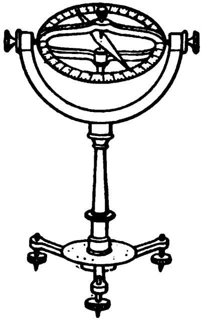


FIG. 207.

The earth as a whole acts in the same way. A needle mounted so that it can move in a vertical plane is called a dipping needle. At a point in British America, near Baffin's Bay, the dipping needle is vertical. Near the earth's equator the needle is horizontal, and as it approaches the south magnetic pole it again is vertical, but with the south-seeking pole down. This variation of the needle from the horizontal is called *inclination.* The amount of the inclination is measured by an instrument called a dipping needle, as is seen in Fig. 207.

399. Magnetic Declination.—A magnetized needle mounted on a vertical axis so that it is free to move in a horizontal plane is called a magnetic compass. Such a compass tends to point toward the north pole of the earth. In very few places, however, does it point to the true geographic north. It generally points either to the east or to the west of the true north. This deviation from the true north is called *declination*, and in some localities the amount of this declination is considerable.

400. Magnetic Survey.—A magnetic survey of the earth enables us to draw a map which shall show the amount of declination and of inclination at different places on the earth's surface. Lines passing through places of equal inclination are called *isoclinic* lines. Lines passing through places having equal declination are called *isogonic* lines. The line passing through places of no declination, where the magnetic north and the geographic north coincide, is called the *agonic* line. The isogonic and agonic lines are shown on the accompanying map.

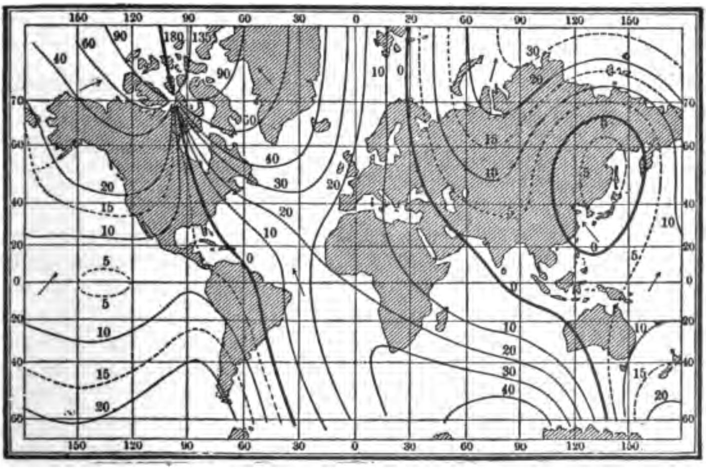


FIG. 208.

401. Magnetic Variation.—Both the direction and the intensity of the earth's magnetism are subject to continual variation, so that the lines mentioned in the previous paragraph are not constant in position. These variations may be divided into five classes.

1. *Diurnal* variation, or the slight to-and-fro motion of the needle which is completed in a day.
2. *Annual* variation, or the to-and-fro motion which is completed in a year.
3. *Eleven-year* variation, or the to-and-fro motion which is completed in eleven years.
4. *Secular* variation, or the to-and-fro motion which is probably completed in a long period of time.
5. *Irregular* variations, called magnetic storms, which accompany outbursts of solar activity.

402. Magnetic Induction of the Earth.—As the earth acts like a magnet in its influence upon a compass, so also its field of force has an inductive influence on magnetizable substances. This is easily shown by the following experiment:

Experiment 103.—Hold a soft bar of iron, about 3 feet long and an inch in diameter, near a magnetic compass. If it is not magnetized, the needle will be attracted no matter which end of the bar is brought near either end of the needle. Now hold the bar parallel to the dipping needle, that is, in the magnetic meridian and dipping at the same angle as the dipping needle, and tap it a few times with a mallet. On now bringing the bar near the needle, it will be found to be magnetized, as one end will attract while the other end will repel the needle. Now hold the bar horizontally pointing east and west and tap it strongly. All the magnetism will now be found to have been discharged, as it will have lost all power of repulsion.

PROBLEMS

1. A magnetic pole of 80 units strength is 15 cm. distant from a similar pole of 30 units strength. Find in dynes the force between them.

2. A pole of 40 units strength acts with a force of 32 dynes upon another pole 5 cm. away. What is the strength of that pole?

3. The force exerted between two equal magnetic poles is 100 dynes when the poles are 8 cm. apart. What is the strength of the poles?

4. The force exerted between two magnetic poles of 9 and 16 units respectively is 4 dynes. How far are they apart?

5. If a magnetized needle is placed on a thin cork floating on water, will it move bodily to the north? Explain in full the reason for your answer.

CHAPTER XXIII

STATIC ELECTRICITY

403. The Word Electricity comes from the Greek word *elektron*, amber, as amber, when rubbed, acquires the property of attracting light bodies. This fact was known for many centuries before any practical application was made of it, having been said to have been discovered by Thales, about 600 B. C. Gilbert, an Englishman, first used the word electricity and was the first to make any extended examination of the subject, as well as to collect what had already been recorded. He published his results in London in 1600, in a book called "De Magnete."

404. Electric Charge Produced by Friction.—If a dry rod of glass, or a stick of sealing-wax, be briskly rubbed with a piece of dry silk or flannel, it acquires the power of attracting or repelling light objects. The glass or wax becomes electrified by means of the friction, or acquires an electric charge.

Experiment 104.—Suspend by a silk thread a piece of fine wire bent in the form of a stirrup. Hang in the stirrup a wooden ruler and bring an electrified glass tube or rod near it. The ruler will be attracted. Now replace the ruler by an electrified glass tube. When the ruler is brought near the tube, it moves as if attracted by the ruler.

It is, therefore, evident that each body is attracted by the other or that the action is mutual.

Experiment 105.—Cut a piece of elder pitch into a ball; tie it to a piece of silk, and suspend it from any support. Try the effect of rubbing different bodies together, and holding them near the pith-ball, to see whether they are electrified.

405. Effects Produced by Electric Charges.—If a body possessing an electric charge, such as a rubber comb which has been briskly rubbed with a silk handkerchief, be brought near the face, a creeping sensation will be experienced, as though cobwebs were touching it. If the electrified body be brought near a blunt metallic conductor, or a knuckle of the hand, the body will be discharged, and a faint bluish spark will pass to the metal or to the hand, with a slight crackling sound. The faint light and feeble sound in this case are of the same character as the lightning flash and the thunder peal, which attend the discharge of a cloud to a neighboring cloud, or to the earth. The science which treats of electric charges and their effects is called *electrostatics*.

406. Electrostatic Attractions and Repulsions.—Attractions and repulsions between electrified or charged bodies may be conveniently shown by means of a pith-ball, suspended by a silk thread from any suitable support, as shown in Fig. 209. If a rod of glass, that has been rubbed with a dry silk handkerchief, is brought near the pith-ball, the latter is attracted to the glass, as shown at A. As soon as the pith-ball touches the glass rod, it is repelled from it, as shown at B, and if not allowed to touch the ground, or any ground-connected conductor, will

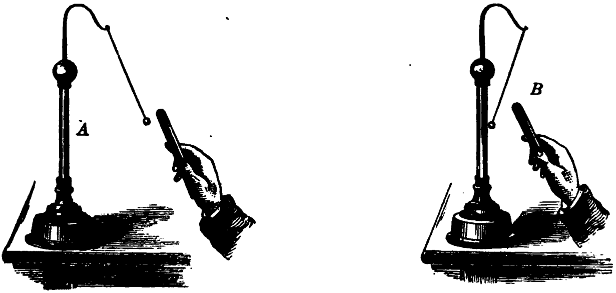


FIG. 209.

continue to be repelled. If, however, it touches such a body, it will again be attracted to the rod and again repelled.

If another electrified body, as a piece of sealing-wax rubbed with flannel, be brought near the pith-ball while it is quietly hanging from its support, it will be attracted and repelled as it was by the glass. If, however, while the pith-ball manifests repulsion for the electrified glass, the electrified sealing-wax be brought near it, it is at once attracted; or, if it be repelled by the wax, it is attracted by the glass.

Any substance electrified by friction acts either like the glass or like the wax. We conclude, therefore, that there are but two kinds of electric charge or excitement; viz., one like that excited in glass rubbed with silk, and one like that excited in wax rubbed with flannel. The former is called a *positive charge* and the latter a *negative charge*. Positive charges are generally represented by +; negative charges by −.

The law of electrostatic attractions and repulsions may be stated as follows: *Like charges repel; unlike charges attract.*

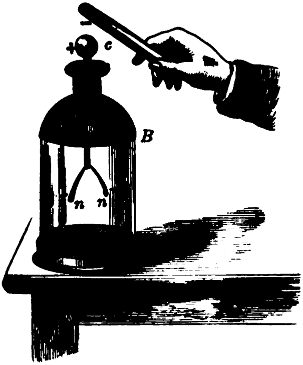


FIG. 210.

407. Electroscope.—The character of any electric charge is determined by means of an instrument called an *electroscope*. The pith-ball, shown in Fig. 209, is a simple electroscope. A better form, however, consists of two small strips of gold leaf, *n*, *n*, Fig. 210, attached to a metal rod, terminating in a metal ball *c*. The gold leaves and rod are placed in a glass jar *B*, inside of which the air can be kept free from moisture. If the ball be touched by an electrified body, the gold leaves receive a charge of the same kind as that in the electrified body, and are, therefore, repelled.

To determine the character of any charge by means of the electroscope, the gold leaves are repelled by a known charge, say positive; and, while the leaves are thus diverged, the charge of unknown character is brought near the ball *c*, and the movements of the gold-leaves carefully observed. If they are still further repelled, the charge of the body is positive; if, however, the leaves approach each other, the charge is negative.

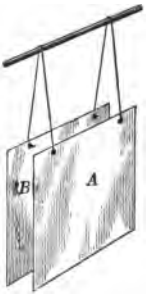


FIG. 211.

Experiment 106.—Suspend *A* and *B*, two pieces of gold or silver paper, about two inches square, by pieces of sewing silk to a rod or other support, as shown in Fig. 211, so that they shall be directly opposite each other. They will form an excellent electroscope. If the leaves be touched by an electrified body, they will be repelled; and if the air be dry, will continue to stand apart for a long time.

408. Equal Quantities Produced at the Same Time.—

Experiment 107.—Fit a small flannel bag to the end of a piece of sealing-wax (Fig. 212) and attach a silk string to the bag. Twist the bag around the wax a few times to electrify the bag and wax, and then present both, just as they are, to the electroscope. No effect will be seen. Now remove the bag by means of the silk string, and the wax will be found to have a charge upon it, while the bag when presented to the electroscope will also be found to be electrified, but with the opposite kind.

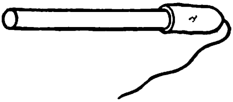


FIG. 212.

This experiment shows, therefore, that when one kind of electrification is developed, the opposite kind is also produced. Since the charges exactly neutralize each other, they must be in equal quantities.

409. Positive and Negative Charge.—The kind of electrification produced by friction, that is, whether positive or negative, depends on the bodies that are rubbed together.

In the following list the different substances are so arranged that each will be *positively charged* if rubbed by any body which *follows it*, and *negatively charged* if rubbed by any body which *precedes it.*

1. Cat's skin.
2. Woolen fabrics.
3. Glass.
4. Cotton.
5. Silk.
6. The hand.
7. Wood.
8. Sealing-wax.
9. Hard rubber.

Thus, if glass be rubbed with flannel or cat's skin, it becomes *negatively charged;* but if rubbed with cotton or silk, it becomes *positively charged.*

The rubber is always oppositely electrified to the thing rubbed. Glass rubbed with silk is positively electrified, while the silk is negatively electrified.

410. Conductors and Insulators.—

Experiment 108.—Connect the knob of a gold-leaf electroscope with an insulated conductor by means of a copper wire. Touch the conductor with a rod that has been electrified by friction. The leaves will immediately diverge, showing that the charge has been transferred along the wire. Replace the wire by a silk thread and repeat the experiment. The leaves will not diverge. If a moistened thread is used instead of a dry one, an effect will be noticed, but it will be less than when the wire is used.

This experiment shows that there is a difference in substances as to their power of allowing electrification to travel or spread over them. Those which, like the wire, carry the charge easily are called *conductors*, while those which do not allow it to pass are called *non-conductors* or *insulators.* No sharp line can be drawn to divide substances into one or the other of these classes. Metals, carbon, and the solutions in water of acids, bases, and salts are good conductors. Glass, paraffin, porcelain, mica, sulphur, and hard rubber are examples of good insulators.

411. Nature of Electricity.—Notwithstanding all the work that has been done by many investigators, we do not yet know *what* electricity is. This is not so strange, however, as it may appear at first sight. Man has known for many centuries the effects of gravity and for many centuries has been able to state the laws according to which it acts. But we do not yet know the *cause* of gravity. Or, to go still further back, most men, since the beginning of things, have believed that they have lived in a material world, and that they were surrounded by substances of real existence which they could see or feel or taste or smell. Yet even to this day we do not know what matter is. It is not then so strange that a substance like electricity has as yet eluded our knowledge.

Several hypotheses have been proposed to account for the phenomena of electricity. Symmer proposed a *two-fluid hypothesis* which assumed that there were two weightless electric fluids of opposite kinds. These exist combined in all bodies in equal quantities until they are disturbed by friction. When separated, they show the phenomena of electrification, but as they neutralize each other, when they come together, the body loses all evidence of electrification.

Franklin proposed a *single-fluid hypothesis*, according to which there is a single electric fluid distributed uniformly in all neutral bodies. When two bodies are rubbed together, one acquires more, and the other less, of the fluid, than the average, and they, therefore, each show signs of electrification, but of opposite kinds.

A more recent theory, and one which seems destined to lead to a more definite knowledge of matter as well as of electricity is called the *electron theory*. According to this theory, electricity is atomic in nature, as we have long believed matter to be. These atoms of electricity are called corpuscles or electrons. They mutually repel each other, thus being opposite to matter in their action. When glass is rubbed with silk, some electrons are withdrawn from the glass by the silk. The excess of electrons on the silk give it its electric charge. Therefore, a negative charge means an excess of electrons. The glass having lost some electrons also has an electric charge which is called positive. It will be noticed that this is an awkward method of naming the charges, but it is the result of the arbitrary assumption stated in Par. 406, that the charge on the glass when rubbed with silk is positive.

412. Electrostatic Induction.—If an insulated conductor, such as the cylinder *A B*, Fig. 213, be brought near a positively charged body *C*, the cylinder will acquire a negative charge at the end *A*, nearest *C*, and a positive charge at the end *B*, farthest from *C*. The pith-balls attached to the cylinder *A B* will show that these charges are greatest at the extremity, and practically absent at the middle part. Induction produced in this way by an electric charge is called ***electrostatic induction.***

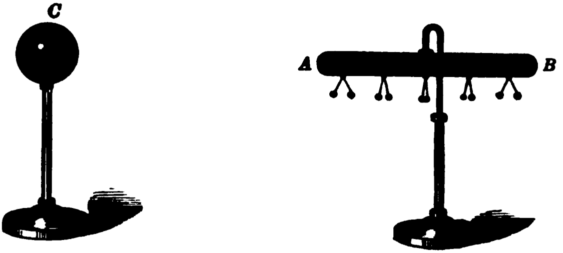


FIG. 213.

Electrostatic induction takes place through the air or other non-conducting medium between *C* and *A B*. Any medium which thus permits electrostatic induction to take place through it is called a ***dielectric.*** All non-conductors or insulators are dielectrics.

413. Explanation of Charging by Induction.—According to the two-fluid hypothesis, the cylinder *A B*, before it was brought near the charged body *C*, contained equal and opposite charges of positive and negative electricity, and was, therefore, neutral. When brought near the positive charge on *C*, the fluids separated, the unlike negative kind being attracted to the end *A* nearest *C*, while the like positive kind was repelled to the end *B* farthest from *C*. Both ends of the cylinder, therefore, gave evidence of electrification. If the charged body *C* was removed, the two fluids again neutralized each other. If, however, while the charged body *C* is present, the cylinder is connected to the earth by touching it with the hand or with a wire, the positive charge is repelled still further, that is, to the earth, and only the negative charge remains attracted or bound at *A*. If the hand is first removed, and then the charged body *C*, the negative charge which is held at *A* will spread all over the cylinder, and it will all be negatively charged. Therefore, a body touched while under the "influence" of another body acquires a charge of the opposite nature.

According to the electron theory the positively charged body *C* was deficient in electrons. When brought near the metal cylinder *A B*, in which some of the electrons were free to move, it attracted the free electrons to the end *A*, making it negatively charged, and left the end *B* with a deficiency of electrons and, therefore, positively charged. When the cylinder is touched while under the influence, the deficiency of electrons is supplied by a flow from the earth. It will be noticed that this theory gives an explanation very similar to that of Franklin except for the reversal of the terms negative and positive.

414. Cause of the Attractions and Repulsions of Excited Bodies.—Alternate electric attractions and repulsions are the results of electrostatic induction. If an unelectrified pith-ball *B*, Fig. 214, be brought near a conductor *A*, charged with positive electricity, it is at once electrified by induction. The side of

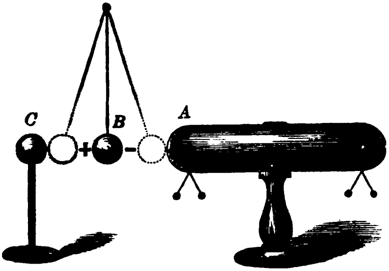


FIG. 214.

the pith-ball nearer A, receiving an opposite charge to that of A, the ball is *attracted* to the conductor. As soon as the ball touches the conductor, it receives a positive charge and is, therefore, repelled. If, now, it should touch a ground-connected body, as C, it will be again attracted and repelled as before.

415. Distribution of an Electric Charge.—All the electric charge on an insulated conductor lies on the outside of the conductor. If an insulated hollow sphere, provided with a hole in the top, is charged with electricity, a small metallic disc attached to the end of a glass rod, called a *proof-plane*, if touched to the outside of the sphere at any point, will take away a small charge of electricity, as may be proved by an electroscope. But if touched to any part of the inside of the sphere, it will be found to contain no electric charge, all the charge of the sphere residing on its surface. This is true only of an electric charge. When the electricity is in steady motion, as an electric current, then it passes through the whole substance of the conductor.

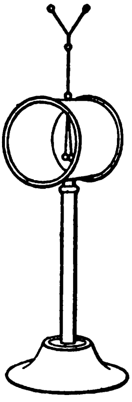


FIG. 215.

This fact may also be shown by an experiment with a hollow brass cylinder mounted on an insulating stand, as shown in Fig. 215. The cylinder is provided with two sets of pith-balls to act as electroscopes, one being mounted on the outside of the cylinder, and the other on the inside. When an electric charge is given the cylinder, even if it is given to the inside, it all immediately goes to the outside, as is shown by the fact that only the pith-balls attached to the outside show any divergence.

Faraday proved on a large scale that the electric charge is entirely on the surface. He constructed a hollow cube of wood, 12 feet on a side, and covered it with tin foil. This was insulated and connected to a powerful electrical machine. He took his most delicate electroscopes into the "room," and had it charged so highly that large sparks were coming from it, but he could detect no charge whatever on the inside.

If an electroscope is placed in a cage of wire screen or gauze, as shown in Fig. 216, it will show no effect when charged bodies are brought near it.

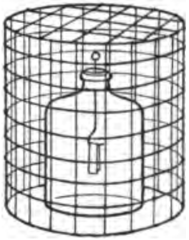


FIG. 216.

416. The Influence of Points on an Electric Charge.—In a charged insulated sphere, the electric charge has the same value over all parts of the surface; but if the excited conductor be egg-shaped, then the charge is greatest near the point of the egg, and this will be found to increase with the sharpness of the point.

Experiment 109.—This is easily proved by means of an electroscope and the proof-plane. When the proof-plane is touched to different parts of a charged insulated sphere, the effect when brought to the electroscope will be the same. But when the proof-plane is touched to the different parts of an insulated egg-shaped conductor, and then brought to the electroscope, the effect will be greater after touching its parts where the curvature is greatest, that is, when it is nearest to the pointed end.

The amount of the charge is evidently greater on the pointed end than on the rounded end. In other words, the electric density is greater on the pointed end. By electric density is meant the quantity of electricity per unit area. Evidently, therefore, if the surface is increased while the quantity of electricity remains the same, the density will decrease and vice versâ.

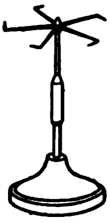


FIG. 217.

When the area becomes very small, as at a point, the density may become so great that the electricity is discharged into the air. Conductors intended to retain an electric charge are, therefore, made blunt or rounded, so as to prevent the loss of charge.

Experiment 110.—Connect an electric whirl (Fig. 217) to one pole of an electric machine and ground the other pole. Work the machine and notice the result.

417. Unit Charge.—When two bodies charged with the same kind of electricity are brought near each other, they mutually repel. This action may be used as the basis of a method for measuring the quantity of electricity. *Unit charge* is defined as the quantity of electricity that will repel an equal and like charge with the force of one dyne when at the distance of one centimetre in air.

Coulomb found that when the size of the charged bodies is very small as compared with the distance between them, the force is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

This is expressed by the formula—

$$F = \pm \frac{q\,q'}{d^2}. \quad (37)$$

If the charges are of the same kind, the force will be a repulsion, and the sign will be positive; if they are of the opposite kind, the force will be an attraction and the sign will be negative.

418. Potential.—When unequal charges of electricity are given to like insulated conductors, they are in such a condition that there is a tendency for a flow of electricity to take place from one to the other. If they are connected by a conductor, there will be a current produced, and electricity will flow from one of the charged bodies to the other. This condition is known as *difference of potential*, frequently abbreviated to P. D.

As a standard of measurement, the earth is assumed to have zero potential. A body charged positively is assumed to be at a higher potential than the earth, while a body charged negatively is assumed to be at a lower potential. Potential may be likened either to temperature or to water level. When two bodies at different temperatures are brought in connection, one will gain heat and the other will lose heat until they are at the same temperature. Here the usual standard of measurement, the zero potential, is the temperature of melting ice.

If two vessels of different heights are filled with water and connected by a pipe opening into the bottom of each, water will flow from the one of higher level to the one of lower level, until the level of the two vessels is the same.

Difference of potential between any two points is measured by the work done in moving unit positive quantity of electricity from one point to the other against the electric forces.

419. Capacity.—When we speak of the capacity of a quart mug for water, we mean the amount of water that will fill it full. As water cannot be piled up, we do not need to limit the definition. If we speak of the capacity of a bushel measure for wheat, however, we need to state that it is the amount of wheat it will hold when "struck" by a board drawn across the surface; for wheat can be heaped up, so that a "struck" bushel and a "heaped" bushel would not be the same in amount. In speaking of the electrical capacity of a conductor a limitation is still more necessary. The conductor is said to be electrically "full" when its potential is unity. The capacity of a conductor is, therefore, the quantity of electricity required to raise its potential to unity. This is expressed by the formula—

$$C = \frac{Q}{V}, \quad (38)$$

in which C means capacity; Q, quantity; and V, potential (measured in volts).

420. Electric Machines.—The Electrophorus.—The simplest form of electric machine, the *electrophorus*, consists of a plate A, Figs. 218 and 219, of brass or other metal, attached to a glass rod, and a plate of resin *B*, placed in a metallic dish. The resin is negatively excited by rubbing it briskly with a piece of cat-skin. The plate *A*, held by the glass handle, and placed over the resin, as shown in Fig. 218, becomes electrified by induction, the side nearest the resin being positively charged, and the side farthest from it, negatively charged. If *A* is now raised from the resin without previously touching it to any conductor, it will be found to possess no charge, since the electricity on the positive side of the disc flows toward the negative side and neutralizes it. If, however, the disc be touched by the finger, as shown in Fig. 219, it will, when raised from the resin, possess a free positive charge.

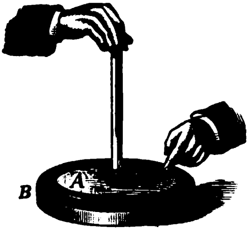


FIG. 218.

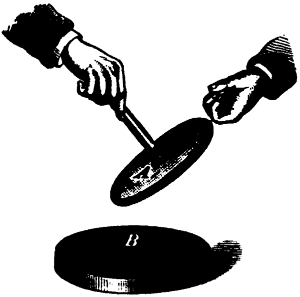


FIG. 219.

The explanation of the process of charging is entirely similar to that already given in Par. 413 for charging a body by induction.

After the disc has been touched, but before it has been lifted, it possesses no potential energy. When it is lifted, however, work has to be done in separating the two unlike charges. The disc, therefore, contains energy which produces the light and heat when it is discharged.

Experiment 111.—An electrophorus may be made as follows: Place in a tin pie-plate, in equal parts, rosin and gum-shellac, sufficient in quantity, when melted, to nearly fill the plate; place the dish over a fire, and *very gradually* melt the rosin and shellac, at the same time stirring so as to break air-bubbles. When melted, set the dish on a flat support to cool. Now cut a disc of wood *smaller in diameter than the rosin surface of the plate;* bore a hole in the middle of the wood and cement in it a glass rod or tube. Paste tin foil over the wooden disc, covering it completely, and remove any rough ends by smoothing the foil with the finger-nail. To operate, rub the rosin plate with a bit of silk or cat-skin, and place the tin-foil disc on the rosin, and touch it with the hand. On removing the disc a spark, or discharge of positive electricity, may be taken from it by the knuckle. When the rosin-plate has once been charged by rubbing, an indefinite number of sparks may be obtained by placing the disc each time on the rosin, and touching with the finger, as before. When the air is cold and dry, as in winter, and the glass handle clean and dry, sparks of considerable length may be obtained.

421. The Plate Electrical Machine.—This machine consists of a circular plate of glass *A*, Fig. 220, mounted on an axis, on which it may be turned by means of an insulated handle *C*. At *D*, a rubber, of piano felting or chamois skin, is pressed by brass springs firmly against the plate. The rubber has generally an *amalgam* spread over its surface, and is in electric contact with an insulated conductor *E*, called the negative conductor. A series of metallic points *F* connected with an insulated con-

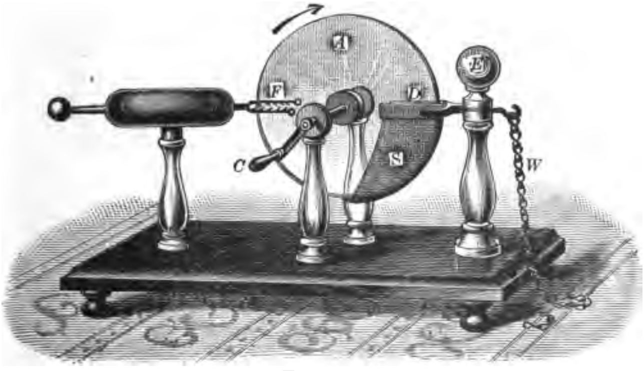


FIG. 220.

ductor *O*, called the positive conductor, is placed near that part of the plate diametrically opposite the rubber, as shown. On turning the handle, the friction of the rubber gives the glass a positive charge and the rubber a negative charge. The negative conductor is now charged by the rubber, while the electricity on the glass, coming opposite the points, attracts to them an equal and opposite negative charge. This negative charge streams from the points, neutralizing the positive charge on the glass and leaves an equal positive charge on the positive conductor *O*. The lower half of the plate is loosely covered by a bag of silk, *S*. When only positive electricity is desired, a chain, *W*, connects the negative conductor with the ground.

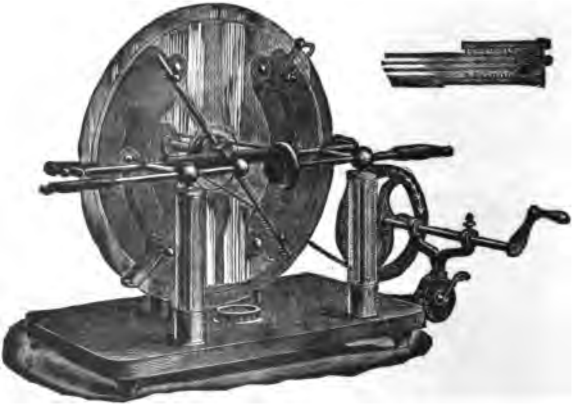


FIG. 221.

A more powerful form of machine, called an ***induction machine***, is shown in Fig. 221. This form is called the Töpler-Holtz machine. It is practically a revolving electrophorus.[1]

422. Condensers.—

Experiment 112.—Place a piece of smooth tin-foil on a plate of glass supported on a glass tumbler or other insulator. Charge the tin-foil by means of an electrophorous, counting the number of sparks it will take. Discharge the tin-foil and remove the glass plate from the tumbler and put it on a piece of tin-foil lying on the table and connected by a chain or wire to the earth (gas- or water-pipe). Again charge the tin-foil and notice that it will require many more sparks than it did before.

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[1] For detailed explanation see S. P. Thompson's "Elementary Lessons in Electricity and Magnetism," p. 55.

As the tin-foil will receive sparks from the charged disc until it is at the same potential, the second arrangement must have increased its capacity very much, as a greater quantity of electricity was required to raise it to the same potential.

Experiment 113.—Connect an insulated metal plate by a wire with an electroscope. Charge the plate slightly, and note the divergence of the leaves of the electroscope. Bring near the charged metal plate a second plate connected to the earth. The leaves of the electroscope fall, showing that the potential of the charge has fallen. But if there has been no leak, this fall of potential means that the capacity has been increased.

The presence of the plate connected with the earth has increased the capacity of the first plate, so that the same quantity does not maintain it at the same potential. The apparatus used in these experiments are forms of *condensers*.

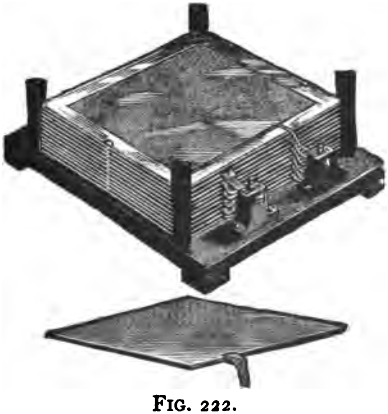

FIG. 222.

In practice the condenser usually takes the form of a pile or bundle of metallic plates, separated by thin sheets of mica, oiled silk, or paraffine paper. A form of condenser is shown in Fig. 222. The capacity of such a condenser increases with the area of the metallic plates and the thinness of the insulating sheets. In order to discharge a condenser, it is necessary to connect the opposite terminal coatings by some conductor. The discharge occurs as a bright flash accompanied by a loud detonation. It can be shown that such a discharge does not consist of one single discharge, but of a number of separate discharges that are alternately oppositely directed.

A drawing from a photograph of such a discharge, made by means of a rapidly revolving mirror, is shown in Fig. 223.

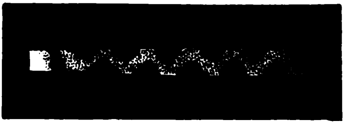

FIG. 223.

423. The Leyden Jar.—In 1745 von Kleist, of Pomerania, while experimenting with a frictional electric machine, hung a small vial containing mercury on one of the prime conductors of the machine. The vial was supported by a bent wire, passing through the cork of the bottle, and dipping down into the mercury. While attempting to remove the bottle, he received what he considered a severe shock. He thus discovered what is now known as the *Leyden jar*. The Leyden jar usually takes the form shown in Fig. 224, where the lower part of a glass jar is coated on the inside and outside with tinfoil. The inside coating is in connection with the brass knob, *A*, by means of the chain *E*. To charge the jar, it is held in the hand which grasps the outer coating, while the knob *A* is brought near the conduc-

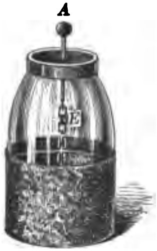

FIG. 224.

tor of an electrical machine, and a number of sparks passed into the jar. If, now, one hand be placed on the outer coating, and the other on the knob A, a discharge will pass through the body and give a more or less severe shock. The discharge may be more conveniently done by means of a discharging rod consisting of two hinged pieces of brass with an insulated handle.

A *battery* of Leyden jars consists of a number of jars having their inner and outer coatings respectively connected with one another so as to act as a single large jar. The discharge from a Leyden jar may be passed through a number of persons joined hand to hand, the person at one end of the line touching the outside coating of the jar, and the person at the other end, the knob. The discharge from a very large battery may prove fatal.

424. Action of Leyden Jar.—The Leyden jar is, in reality, a form of condenser. The presence of the outer coating connected by the hand or chain to the earth increases the capacity of the inner coating. When a charge is given the inner coating by the machine, it acts inductively through the glass on the outer coating. The unlike kind is attracted to the glass and the like kind repelled to the earth. This is the reason for always earthing the outer coating. The attraction of the unlike kind prevents the potential of the inner coating from rising and, therefore, it takes a much larger quantity of electricity; that is, its capacity is increased.

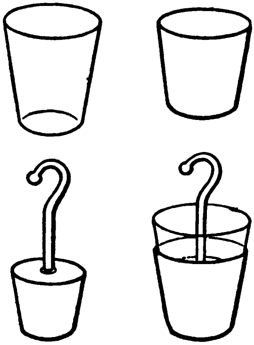

FIG. 225.

425. Seat of the Charge.—

Experiment 114.—A Leyden jar which can be taken apart may be readily obtained. (See Fig. 225.) Set the jar up and charge it as usual. Now take it apart and examine the parts separately. The two metallic coatings will show no evidence of a charge when brought near the electroscope, and when connected by a discharging rod no spark will pass. The glass vessel will show signs of electrification when brought near the electroscope and when the metallic coatings are replaced, the jar can be discharged as usual.

The charge was evidently not on the metallic coatings, but on the glass. The metal merely acts as a conductor in charging and discharging. The charge on the glass produces a strain which may be sufficient to break the glass if it is thin and the charge great. When the jar is discharged, the strained glass does not at once assume its normal shape. Hence successive small discharges may be obtained, called the residual charges.

426. Atmospheric Electricity.—The atmosphere usually contains a positive charge, though it sometimes changes rapidly to negative on the approach of clouds or in stormy weather. The charge is least near the earth's surface, and increases with the altitude.

The charges on the minute drops of water in the air are on the surface. As many of these drops unite to form larger single drops the charge on unit surface will increase, since the surface of a larger drop will not be equal to the sum of the surfaces of the smaller drops of which it is composed. The charge, however, on the larger drops is exactly equal to the sum of the small charges, and will all be found on the surface of the larger drop. The quantity of charge per unit area, that is, the density of charge, is, therefore, increased, and the potential of the drop rises.

427. Lightning.—When the electric charge on the surface of the drops of moisture in a cloud has reached a sufficient P. D., a lightning flash may occur. When such a cloud comes near the earth, the ground below it becomes oppositely charged by induction; and when these opposite charges acquire sufficient P. D., they discharge into each other through the air, the flash which accompanies the discharge being called *lightning*. An electrified cloud sometimes discharges into a neighboring cloud which is oppositely charged. When the lightning flash passes, the heat produces a very sudden expansion and compression of the air. This produces a partial vacuum, and the air rushes into this, producing the noise called *thunder*.

428. Lightning-rods consist of stout rods of iron or copper, attached to the outside of the building to be protected, and extending some little distance above its highest point. The upper end of the rod should be pointed, and its lower end should extend deep into the ground, until it reaches permanently damp earth, or some other good conductor of electricity. If underground water- or gas-pipes are in the neighborhood, it is well to connect the rod to them. If the roof of the building be of metal, such as tin or copper, it should be connected with the rod. The rod should be of sufficient thickness to conduct to the earth, without being melted, the heaviest discharge that may strike the building. For all oscillatory discharges, a *stranded conductor*, *i. e.*, a conductor composed of separate conductors, is better than a single conductor. A lightning-rod, not well electrically connected with the earth, is a source of danger rather than a protection.[1]

429. Experiments in Frictional Electricity.—A number of instructive electrical experiments may be shown with easily contrived apparatus. The student is earnestly advised to make the information his own, as far as possible, by verifying facts by experiment.

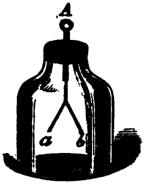

FIG. 226.

Experiment 115.—Cut two strips of gilt paper, *a* and *b*, about one inch long, and connect them, as shown in Experiment 107, but with *linen* or *cotton* thread instead of silk. Stick a wire through a cork of a wide-mouthed bottle, and tie the threads to the ends of the wire, leaving the discs hanging by about ¼ inch of thread. Solder a smooth metal button, *A*, to the end of the wire, and put the cork in the bottle, so that the pieces of paper shall be inside the bottle, as shown in Fig. 226, first, however, being sure that the bottle is *perfectly dry* by heating it on a warm stove. The cork also must be perfectly dry. Run melted sealing-wax over the top of the cork, so as to prevent any moist air from afterward getting into the bottle. This apparatus will now serve as an electroscope.

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[1] See S. P. Thompson, "Elementary Lessons in Electricity and Magnetism," p. 320, for a summary of best conditions for lightning-rods.

Experiment 116.—Attach a long metallic wire to the button *A* of the electroscope just made. Excite the electrophorus described in Experiment 111, and touch the far end of the wire with the tin-foil disc. The leaves *a* and *b* will at once diverge, showing that the wire has conducted the electricity to them. Try the same with a dry silk thread, and prove that it is a poor conductor.

Experiment 117.—In the corners of a square piece of wood bore four holes, large enough to insert the necks of four beer bottles. Stand a person on this *insulating stool*, and charge him with electricity from the electrophorus by giving him 15 or 20 sparks from the tin-foil disc. If, now, the knuckle be approached to any part of his body, an electric spark will pass from it to the knuckle. While on the stool he can light the gas with the spark from his finger.

Experiment 118.—Place a person on the insulating stool, and let him hold the electroscope, Fig. 226, in his hand, with his finger on the knob *A*. Then strike him on the back with a piece of cat-skin; at every stroke the leaves *a* and *b* will be seen to diverge.

Experiment 119.—Suspend by silk threads *a* and *b*, as shown in Fig. 227, a tomato can, free from sharp edges; attach to the lower side, by *linen* or *cotton thread*, pith-balls *c* and *d*, and you have an insulated conductor.

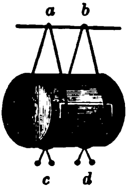


FIG. 227.

Experiment 120.—Make another such conductor, and try the effects of induction as described in Par. 412.

Experiment 121.—Procure a sheet of letter paper, and a smooth pine board somewhat larger than the paper. Heat the board and paper before a fire. Then place the paper on the board, and stroke it briskly with a piece of India-rubber, such as is used for erasing lead-pencil marks. The paper will become strongly electrified. Now lift the paper from the board by one of its edges, and bring it near the wall, and it will be at once attracted to the wall, and will cling to it for several minutes.

Experiment 122.—Electrify the paper as before, and while it is on the board, cut it into strips. Take hold of all the strips at one end, and lift them from the board. Their lower ends will be repelled, and will stand out from one another in an amusing manner.

Experiment 123.—Electrify a piece of paper as before. Remove it from the board, and lay a pith-ball on it. The ball will either be thrown off the paper at once, or it will run to the lower side of the paper, and will then be shot off from it.

Experiment 124.—Place a metal waiter on top of a dry glass goblet. Electrify the paper and place it on the waiter. Apply the knuckle of the hand to the edge of the waiter, and a spark will pass to it. Remove the paper by the edge, and another spark can be taken from the paper.

Experiment 125.—Support a piece of window-glass, about an inch above the surface of a table. Place a few pith-balls under the glass, and rub the top of the glass briskly with a piece of silk or cat-skin. The balls will move about in a curious manner, and some will probably stick to the glass. Stop rubbing, and hold a finger near the glass above the balls, and they will at once fall.

PROBLEMS.

1. Two small insulated spheres, one charged with 20 units of positive electricity and the other charged with 20 units of negative electricity, are placed at a distance of 15 cm. apart. How much is the attractive force between them in dynes?

2. When two small metallic spheres are equally charged and placed 12 cm. apart, they are found to repel each other with a force of 3 dynes. How much is the charge of each sphere in electrostatic units?

3. Two spheres charged one with + 20 and the other with —15 units of electricity are placed at a certain distance apart. They are then brought into contact and afterward placed in their original position. What is the ratio of the forces acting between them before and after the contact.

4. Will a solid sphere hold a larger charge of electricity than a hollow one of same diameter and of the same substance? Why?

5. If a flash of lightning is seen at a distance of 5 miles, how long will it be before the thunder is heard if the temperature is 80° F.?

6. Explain how you would prove that a body is charged with electricity and how you would determine the kind of charge.

7. Tell how you would electrify a metal rod by friction.

CHAPTER XXIV

ELECTROMOTIVE FORCE

430. Electromotive Force.—We have seen (Par. 423) when the outer and inner coatings of a charged Leyden jar are connected by a conductor, a current flows in the conductor. This is due to the P. D. at the ends of the conductor; but the current is momentary, as the P. D. quickly becomes zero. If a continuous current is desired, the P. D. must be maintained by some means. Various methods of maintaining this difference of potential are employed, but they all may be classed under three heads, the voltaic cell, the thermo-electric couple, and the cutting of lines of force, for example, by a dynamo.

In all these cases the difference of potential may be regarded as producing a kind of force which pushes the electricity through the circuit against the resistance. This force is called *electromotive force*, and is usually abbreviated to E. M. F.

431. Voltaic Cells.—When any two dissimilar metals are dipped into a liquid that is capable of acting on one of them, an E. M. F. is produced whose value depends on the nature of the metals and on the nature of the liquid into which they are dipped. Any two substances that are used together for this purpose form what is called a *voltaic couple;* the exciting liquid is called the *electrolyte;* and the entire arrangement a *voltaic cell.* As a rule, couples of carbon and zinc dipped in certain acid electrolytes produce the highest E. M. F.

The production of E. M. F. by chemical action was first noticed by Galvani, an Italian physiologist, who erroneously ascribed the effects produced to the presence of a vital fluid. He was making experiments in which he used the legs of recently killed frogs. Hanging them against an iron balustrade, he noticed that whenever the metal touched a large nerve in the frog's leg, and so brought it into electric connection with the muscles of the leg, the legs violently twitched as in life. He thought that these movements were caused by a vital fluid which came out of the nerve and flowed through the iron into the muscles.

Volta, a distinguished physicist, showed that these movements were due to electricity, and constructed an arrangement called a *voltaic pile* or *battery,* by means of which powerful continuous currents of electricity could be readily produced. This source was named the *voltaic pile,* after his name.

432. A Simple Voltaic Cell.—A simple voltaic cell consists of two plates of different metals immersed in a liquid which can readily act on one of them. One of the simplest forms given to the voltaic cell is seen in Fig. 228, where a plate of zinc and a plate of copper are immersed in water containing sulphuric acid.

If the zinc be pure, as long as the circuit of the cell remains open no action between the liquid and either plate occurs. On closing the circuit, however, an action takes place between the liquid and the zinc, and hydrogen gas, produced by the decomposition of the water, is seen to escape in minute bubbles from the copper, and a current of electricity continues to flow in the direction indicated by the arrows as long as any chemical action continues.

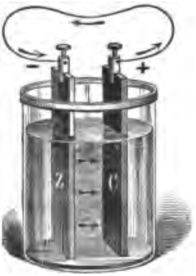


FIG. 228.

In the form of cell shown the *positive pole* or *terminal* is the end of the copper plate that projects out of the electrolyte, and the *negative pole* or *terminal* is the corresponding end of the zinc plate.

It should be noted here that the copper *plate* is the negative plate in the solution, while the zinc *plate* is the positive plate.

Outside the polarity is reversed, the copper being positive and the zinc negative. An inspection of Fig. 228 will show why this must be so. If we define the direction of the current to be from the positive to the negative it will be from the zinc to the copper in the solution and from the copper to the zinc in the outside wire. As a matter of fact, if a sufficiently large proof plane is touched to a copper pole, it will show a positive charge when brought to an electroscope provided with a plate.

433. Theory of Action of Simple Cell.—As hydrochloric acid is chemically a simpler substance than sulphuric acid, let us suppose that our simple cell consists of a plate of zinc and a plate of copper immersed in dilute hydrochloric acid. The smallest portion of hydrochloric acid which can exist is called a molecule. When the acid is dissolved in water, it is believed some of its molecules are split into two portions called *ions*, each with an electrical charge. This action is called *dissociation*. The hydrogen ion has a + charge and the chlorine ion a — charge. When the plates are immersed in the acid and are unconnected outside, bubbles of hydrogen gas arise from the zinc while no action is visible at the copper. Some zinc ions have gone into solution, positively charged, and have pushed out a corresponding number of hydrogen ions so that they escaped in the form of a gas.

The copper is not acted on by the dilute acid, and, therefore, no hydrogen appears at this plate. It is believed that there is no regularity in the motion of the ions in the solution when the plates are unconnected by a wire. When, however, they are joined by a wire, the ions move in a definite direction—the Cl ions carrying a negative charge move toward the positive zinc plate, while the H ions with the positive charge move toward the copper plate. This motion of the ion in a definite direction is called *migration*. When the hydrogen ions reach the copper plate, they give up their charges to it, so that a current flows into the wire from the copper to the zinc. The carrying of the ions in the solution is called *electrolytic conduction*. It is apparently similar to convection in heat. The solution which thus carries a current is called an *electrolyte.*

434. Local Action.—Commercial zinc always contains some impurities, such as carbon and iron. When a piece of such zinc is put in dilute acid, the impurities form a voltaic couple with the zinc, and this action goes on even when the circuit outside is broken. This is wasteful, as both zinc and acid are used up, the energy causing heating of the battery. To avoid this the zinc is *amalgamated* by first dipping in dilute acid and then rubbing with mercury. This coats the zinc with an amalgam, in which the impurities are not present, so that the local action is prevented.

435. Polarization.—If a simple zinc-copper couple is connected with some form of measuring instrument, such as a galvanometer, it will be noticed that the original deflection of the needle gradually becomes less. This shows that the current the battery produces is growing less. If the copper is removed, washed, and dried, and then replaced in the cell, the reading of the instrument will return to the original value. This shows that the cause of the falling off of the reading was the accumulation of hydrogen on the copper plate.

This action is called *polarization.* The collection of hydrogen on the plate causes the current strength to fall off for two reasons.

(1) It increases the internal resistance of the cell. It does this because, when the plate is more or less covered with hydrogen, there is less copper area to act as a conductor, and also because hydrogen itself is not as good a conductor as copper.

(2) The E. M. F. of the cell is lowered, since when the copper is coated with hydrogen, the cell really becomes a zinc-hydrogen battery, and the P. D. of such a combination is less than that of a zinc-copper one.

If a cell is to be of any practical value, polarization must be prevented. The many varieties of cells in use are examples of the different ways in which the problem has been attacked. Three of these will be described as typical of all. In all non-polarization cells the aim is to prevent the accumulation of hydrogen on the negative plate.

436. The Daniell Cell.—This cell consists of a plate of zinc immersed either in a solution of zinc sulphate or in dilute sulphuric acid, and a plate of copper immersed in a solution of copper sulphate. As these solutions would mix they are kept apart by a porous cup or by permitting the lighter solution of zinc sulphate to float on the denser solution of copper sulphate.

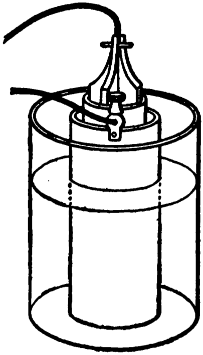


FIG. 229.

Fig. 229 shows the cell with the porous cup. When the circuit is closed, the zinc tends to go into solution in form of ions (see Par. 433) positively charged. These tend to displace the hydrogen ions which migrate with their positive charges toward the copper plate. This plate is, however, surrounded by a solution of copper sulphate containing copper ions. The hydrogen ions give up their charges to the copper ions, which in turn carry the charges to the copper plate. The result is that copper is deposited on the copper plate. No polarization occurs, therefore, as neither the internal resistance nor the E. M. F. of the cell varies. The E. M. F. of this cell is a little more than 1 volt, but on account of the porous cup, the internal resistance is rather high—from 1 to 6 ohms (see Par. 452).

Fig. 230 shows the form of a cell, called the gravity cell, in which the solutions are prevented from mixing by placing the heavy copper sulphate at the bottom. The action of the cell is entirely like the one with the porous cup.

The Daniell cell has had a very wide use in the past, especially in the gravity or crow's foot form (so called from the shape of the zinc plate) on account of its non-polarization. In telegraphic work this cell is now replaced to a great extent by the dynamo or the storage battery.

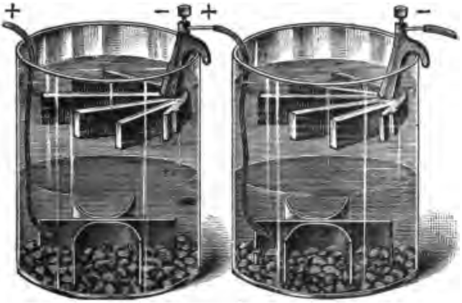


FIG. 230.

437. The Bichromate Cell consists of a plate of zinc between two plates of carbon immersed in a solution of bichromate of potassium or of sodium in dilute sulphuric acid. The solution has the power of oxidizing the hydrogen and thus preventing it from collecting on the carbon. As the plates are large and close together, the internal resistance is small. The E. M. F. of the cell is about two volts. However, the polarization is not entirely prevented, so that the E. M. F. falls off on a closed circuit.

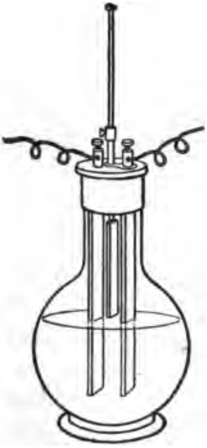


FIG. 231.

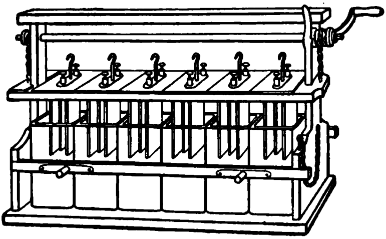


FIG. 232.

The liquid in the cell does not remain unaltered, so that frequent renewals are necessary. As the zinc is attacked by the solution even on open circuit, it has to be withdrawn from the cell when not in use. Fig. 231 shows the Grenet form of the cell and Fig. 232 a group of cells arranged in what is known as a plunge battery.

438. The Leclanché Cell (Fig. 233) consists of a rod of zinc dipping into a solution of ammonium chloride (sal ammoniac) and a plate of carbon with a mixture of manganese dioxide and coke lightly packed around it. This cell has an E. M. F. of about 1.5 volts. There is no action on an open circuit, so that it is very useful where a momentary current only is needed, as in ringing bells in a house. When a circuit is closed, the zinc dissolves to form the chloride, and the displaced ammonium ions, NH_4, migrate to the carbon. Here they break up into ammonia and hydrogen. The manganese dioxide oxidizes the hydrogen to water, thus preventing the polarization. However the oxidation is not rapid, so that on a closed circuit the E. M. F. rapidly falls. When allowed to rest on an open circuit, the cell slowly recovers.

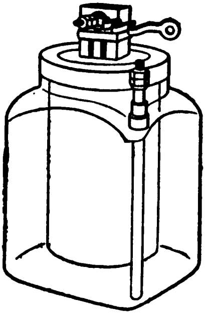


FIG. 233.

439. Thermo-electric Couples.—If two bars of unlike metals, such as copper and iron, or antimony and bismuth, be soldered together at one end, the other ends connected by a conductor, and the soldered end heated, an E. M. F. will be produced and a current of electricity will flow in a certain direction through the circuit so provided. If the soldered end be cooled, a current of electricity will also be produced, but in the opposite direction. Such an arrangement is called a *thermo-electric couple* or *cell.* A number of thermo-electric couples so connected as to act as a single electric source is called a *thermo-pile* or *battery.* A thermo-pile is shown in Fig. 234, where the arrangement of each column of couples is shown on the right. If one face only of the pile is heated, an E. M. F. will be produced.

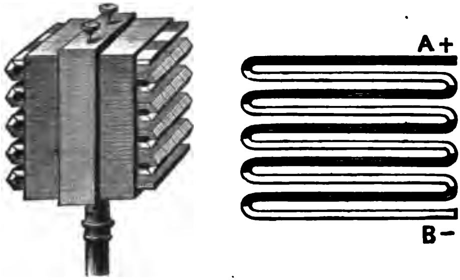


FIG. 234.

Currents of electricity produced in this way by the action of heat will continue to flow as long as there is any difference of temperature between the opposite ends of the bars.

Thermo-electric E. M. F.'s are usually very feeble. They vary with the kind of metals used, and within certain limits, with the difference of temperature between the opposite ends of the couples.

CHAPTER XXV

EFFECTS OF AN ELECTRIC CURRENT

440. Effects Produced by an Electric Current.—The passage of an electric current through a conductor produces various effects, the principal of which are as follows:

1. *Magnetic Effects.*—All conductors conveying electric currents produce magnetic flux, and, therefore, acquire the properties of magnets, being surrounded by magnetic fields.

2. *Thermal Effects.*—The conductor becomes heated. When the current passing through any conducting wire is sufficiently strong, the wire is rendered incandescent, and emits light as well as heat.

3. *Chemical Effects.*—An electric current causes decomposition of certain classes of conductors.

4. *Physiological Effects.*—Involuntary movements of the muscles of an animal are produced by an electric current sent through its body, not only during life, but also for some time after death.

441. Magnetic Flux Surrounding an Active Conductor.—The passage of an electric current through any conductor, no matter what may be the material of which it is composed, is invariably attended by the production of magnetic flux in the space surrounding the conductor. If the conductor is long and straight, this flux flows around it in concentric circular paths. Its direction depends on that of the current through the conductor, and, therefore, changes with that of the current.

The distribution of the flux surrounding an active conductor may be shown, as in Fig. 235, by passing the conductor through the center of a sheet of stiff paper and sprinkling iron filings on it. An examination of the figure will show that the flux-paths surround the conductor in concentric circles whose planes are at right angles to the conductor.

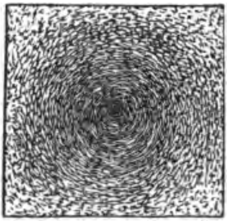


FIG. 235.

The direction of the magnetic flux surrounding a conductor in which a current is flowing may be determined as follows: Grasp the conductor with the right hand (Fig. 236), the thumb pointing in the direction in which the current is flowing. The fingers will then point in the direction of the lines of force. In Fig. 235 if the current is flowing from the observer into the plane of the drawing, the lines of force will then be clock-wise.

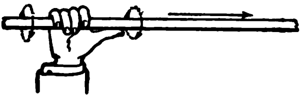


FIG. 236.

If a conductor carrying a current is placed above or below a magnetic needle free to rotate, but at rest in the earth's field, pointing approximately north and south, it will swing out of position and tend to place itself at right angles to the conductor. The right-hand rule again enables the direction of rotation or the direction of the current to be predicted if the other factor is known. Place the right hand with the palm facing the needle and the fingers pointing in the direction in which the current is flowing. The thumb will then point in the direction in which the N pole of the needle will be deflected.

442. Electro-magnets.—If an active conductor be bent in the form of a circle or loop, its magnetic flux will enter the loop at one face and emerge from it at the opposite face. If the active conductor be bent in the form of a *hollow coil* or *helix*, its flux will also enter the coil at one face and leave it at the opposite face.

In either case a change in the direction of the current through the conductor will result in a change in the faces at which the flux enters and leaves the loop or loops.

We have seen that in all magnets the flux emerges at one pole and returns to the magnet at the other pole, after passing through the space outside the magnet. Consequently, a single loop of active conductor, or a number of loops of such conductor, acts as a magnet and has a north-seeking pole at the end at which the flux emerges, and a south-seeking pole at the end at which the flux enters. A magnet produced in this way by an electric current is called an *electro-magnet.* The strength of an electro-magnet, like that of any other magnet, depends on the quantity of magnetic flux passing through the magnet. The quantity of flux produced by any single conducting turn or loop depends on the current strength passing through that loop. If we increase the current strength, we increase the quantity of magnetic flux. If we increase the number of loops, the current strength remaining the same, we increase the quantity of magnetic flux, and, consequently, the strength of the magnet. To increase the strength of an electro-magnet we must, therefore, either increase the current strength or the number of turns or loops.

443. Soft-iron Cores of Electro-magnets.—If a core of soft iron be introduced into a hollow coil or helix, the strength of the magnetic flux produced will be very greatly increased. Consequently, in all electro-magnets a core of soft iron is employed. The flux thus added to the magnet from the iron core is usually greatly in excess of that produced independently from the magnetizing currents.

444. Form of Electro-magnets.—If a bar of soft iron, *N S*, be wrapped with a few turns of insulated wire and connected to a voltaic cell, as shown in Fig. 237, the flowing of the current in the direction indicated by the arrows will produce a N-seeking pole at *N*, and a S-seeking pole at *S*.

As shown in Fig. 237, the current around the *S* pole flows clock-wise and the current around the *N* pole flows counter-clock-wise, the observer facing the poles.

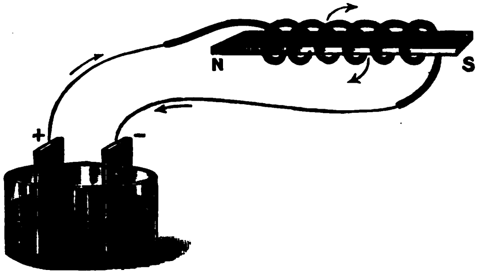


FIG. 237.

Another easy way to remember this is to learn the "right-hand rule." As shown in Fig. 238, grasp the coil with the right hand so that the fingers point the way the current is flowing. The thumb will then point in the direction of the *N* pole.

Electro-magnets are usually made of the horseshoe type, either by bending the bar or core at its middle point, or by winding separate magnetizing coils on separate cores and connecting them by a yoke of soft iron, as shown in Fig. 239. Usually a number of layers of insulated wire are employed as shown in the figure.

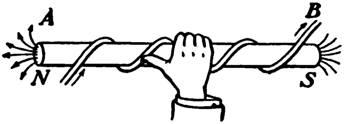


FIG. 238.

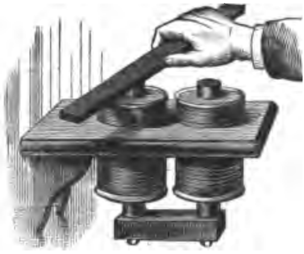


FIG. 239.

445. Uses of Electro-magnets.—An electro-magnet, when provided with a soft-iron core, possesses the valuable property of almost instantly acquiring and losing its magnetism when the magnetizing current is established or interrupted. Electromagnets are extensively employed in a great variety of apparatus, such as in dynamo-electric machines, electric motors, and in telegraphic, telephonic, and signaling apparatus generally. The various applications will be considered later.

446. Thermal Effects.—When an electric current flows through a conductor, it heats the conductor. In the case of a wire, unless the current be very great, the elevation of temperature is almost inappreciable, provided the wire be stout and of good conducting material. If, however, the wire be of small diameter, so as to offer a high resistance in a short length, it may become intensely heated or even melted and vaporized by the current. The temperature attained by the wire depends not only on the heat units developed, but also on the specific heat of the metal and the character of the surface of the wire. The greater the amount of heat which has to escape from each square inch of a surface in a given time, the higher the temperature the wire will attain.

447. Electric Heaters.—The heat produced by an electric current passing through a short conducting path of comparatively high resistance is utilized in the *electric heater*, in *electric ranges* or *stoves*, and in *electric furnaces*. One of the best examples of electric heaters is seen in the heaters employed in some electric trolley cars. Here, coils of wire, placed in convenient situations in the car, serve, when traversed by the current, to heat the cars.

The heating effect of the current is used in *fuse wires* to protect an electric system from the dangers of overloading. A fuse wire is made of an alloy the melting point of which is low. A piece of this is inserted in the circuit and its diameter so chosen that if more current passes than is safe, the wire is heated above its melting point and thus breaks the circuit at this point.

If the heat developed is sufficiently great, light is produced. When a conductor conveying the current from a battery or dynamo is broken at any point, a brilliant flash of light is seen.

If the ends of the wire connected with two pencils of carbon are brought together, and then slowly separated, a brilliant arc or light, called the *voltaic arc*, will continue to pass between the electrodes, unless they be too widely separated.

448. Chemical Effects—Electrolysis.—When an electric current is passed between suitable terminals or *electrodes*, through a conducting liquid, capable of being decomposed by the current, called an *electrolyte*, it decomposes the electrolyte into two constituent parts, which appear at the positive and negative electrodes. This decomposition is called *electrolysis*.

This action may be easily studied by using as the electrolyte a solution of sodium sulphate in water. Place the solution in a glass vessel before the lantern, and insert electrodes of platinum foil after having colored the liquid strongly with neutral (lavender colored) litmus solution. Connect the electrodes with some cells, and evidence of chemical action will immediately appear. At the positive elctrode or *anode* the litmus will turn red and bubbles of oxygen will appear. At the negative electrode or *cathode* the litmus will turn blue and hydrogen will be given off.

This action is explained by the ionization theory as follows: Sodium sulphate is represented by the formula Na_2SO_4. When this is dissolved in water, it is *dissociated* or split into smaller parts called *ions*, each with an electrical charge. The sodium ions have a positive charge and the sulphions (SO_4) have a negative charge. The dissociation was caused by the solution in water and was present before the current was applied, the ions moving about freely, but in no definite direction. When the current was applied, a definite motion of the ions, called *migration*, took place. The sodium ions, carrying positive charges, moved to the cathode and gave up their charges to the platinum electrode. Having lost their charges they became atoms of sodium, which immediately acted on the water to form sodium hydroxide, which turned the litmus blue, and hydrogen gas, which escaped in bubbles. At the same time the sulphions migrated to the anode and gave up their negative charges. As platinum is not attacked by SO_4, it was not dissolved, but the water molecules were decomposed to form sulphuric acid, which turned the litmus red, and oxygen gas escaped.

449. Electrolysis of Water. Electro-plating.—If two platinum strips be made the electrodes of a voltaic battery, and inserted into water which has been rendered slightly acid for the purpose of increasing its conducting power, the current in passing through the solution will decompose it, Fig. 240, and hydrogen will be given off at the cathode, and oxygen at the anode. If the electrodes be dipped into a solution of any salt of a metal, as copper sulphate, the passage of the current will decompose the salt, metallic copper will appear at the cathode, and will be deposited as an adherent metallic film on any conducting surface connected therewith, and a compound of sulphur will be set free at the anode. If the anode be of some metal with which the sulphur compound combines, as, for example, copper, sulphate of copper will be formed, and will thus keep up the strength of the solution. In this way we can deposit strong adherent films of metal on the surface of any conductor; for, if the article to be coated be attached to the cathode of a battery, and dipped into a solution of the metal with which we desire to coat the article, say copper, and the anode be attached to a plate of copper and also dipped into the liquid, when the current passes the salt will be decomposed, and the metal deposited in a uniform layer over the article at the cathode. This process is called *electro-plating*, and by it articles may be coated with gold, silver, copper, nickel, and other metals.

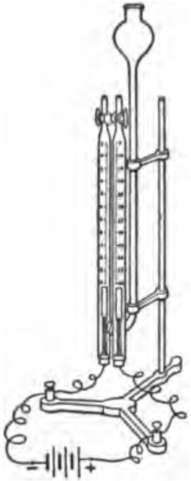
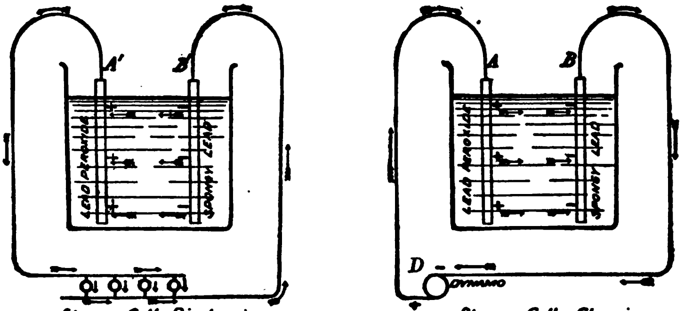


FIG. 240.

Wood-cuts are not used directly for printing, since they would soon wear out. The wooden blocks on which the drawings are cut are pressed into a case filled with a thin sheet of bees-wax, and the impression thus obtained polished with black lead to make it electrically conducting. It is then attached to the cathode of a battery and immersed in a solution of copper sulphate. On the passage of the current the leaded surface of the wax is covered with a thin film of copper, which is an exact reproduction of the drawing on the wooden block. The copper film is removed from the wax mould and stiffened by being backed with stereotype metal, and the form thus obtained used for printing.

450. Storage Cells.—All the various types of voltaic cells which have been considered have zinc as the positive metal. They can furnish a current only as long as zinc remains unused or as the electrolyte has not been destroyed. They are therefore called *primary cells*, as they cannot again be used until the metal or electrolyte has been replaced.



Storage Cell Discharging
X

Storage Cell _ Charging
Y

FIG. 241.

A type of cell in which this difficulty is avoided is called a *secondary cell*, *storage cell*, or *accumulator*. When such a cell is exhausted, no renewal of plates or of electrolyte is required, but a current from a dynamo is sent through the cell in the opposite direction to that of the current furnished by the cell. This process is called *charging*, and the chemical changes which it produces restore the cell to its original condition.

The storage cell in common use consists of a plate of lead and of a plate of lead coated with lead peroxide, dipping into a dilute solution of sulphuric acid. The metallic lead is the cathode and the lead peroxide is the anode. When the cell discharges through an external circuit (Fig. 241, *X*), both plates become covered with lead sulphate and the density of the electrolyte falls, as SO_4 ions are withdrawn in producing this change. When the discharge has proceeded as far as is desirable, the cell is charged by passing a current into it in the opposite direction (Fig. 241, *Y*), so that the anode of the dynamo is connected with the anode of the cell. The chemical changes now proceed in the opposite direction, the positive plate changing from sulphate to peroxide and the negative plate from sulphate to metallic lead. As SO_4 ions are returned to the electrolyte during this process, the density of the solution rises and thus gives one method of controlling the charge.

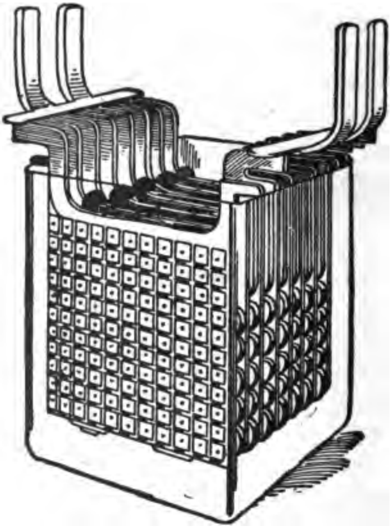


FIG. 242.

As the plates of this cell are large and close together, the internal resistance is low. The E. M. F. being from 2 to 2.5 volts, the cell can, therefore, give a considerable current strength.

A number of pairs of plates are frequently arranged in the same containing vessel (Fig. 242), making a convenient form of storage battery. Such batteries are largely replacing primary cells, as in telegraphic work, and have found a much wider use, as equalizers of the load in trolley power stations.

451. Physiological Effects.—An electric current passed through a recently killed animal causes convulsive movements of the muscles, as in life. Passed through a living animal it produces similar movements. Its passage under suitable conditions is also attended by various physiological actions, some of which may be favorable to the cure of certain diseases. Electricity, however, as a curative agent may do more harm than good, and should never be employed except by a skilful and intelligent physician.

CHAPTER XXVI

ELECTRICAL MEASUREMENTS

452. Ohm's Law.—The law in accordance with which electricity flows or passes through a circuit was discovered by Dr. Ohm, of Berlin, and is known as *Ohm's law*. It may be expressed as follows:

The current which passes through any circuit is directly proportional to the E. M. F. acting on that circuit, and inversely proportional to the resistance of the circuit; or, in other words, the current strength increases as the E. M. F. increases, and diminishes as the resistance increases.

The three electrical quantities just mentioned are measured in the following units. Current strength is measured in *amperes;* a unit named after the Frenchman, Ampére. For electro-motive force, E. M. F., the unit is the *volt*, named after Volta, the Italian. The *ohm* is the unit of resistance, from Ohm, a German physicist.

The three units are defined as follows:

The ohm is the resistance of a column of mercury 106.3 cm. in length, and having a mass of 14.4521 grams, at 0° C. The cross-section is about 1 sq. mm. Two miles of ordinary copper trolley wire have a resistance of about one ohm, as has also one foot of No. 40 copper wire.

The ampere is the current that will deposit, in one second, 0.001118 gram of silver from a solution of silver nitrate in water.

The volt is that E. M. F. which will produce a current of one ampere in a conductor the resistance of which is one ohm. This is about equal to the E. M. F. of a Daniell cell.

The ampere may also be spoken of as the current that will flow in a conductor having a resistance of one ohm, if an E. M. F. of one volt is maintained at its terminals.

The ohm is then the resistance of a conductor in which an E. M. F. of one volt maintains a current of one ampere. These relations, as stated in Ohm's law, are all expressed by the formula

$$C = \frac{E}{R}. \quad (39)$$

in which C = current; E = E. M. F., and R = resistance.

This may also be expressed: $\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}$.

In addition to the three fundamental units as given there are numerous others, but two of which need be mentioned here. The *coulomb* is the unit of quantity. One ampere flowing in a circuit carries one coulomb per second. The *watt* is the unit of power. One ampere flowing under an E. M. F. of one volt develops one watt.

$$W = V \times A. \quad (40)$$
$$\text{Watts} = \text{Volts} \times \text{Amperes}.$$

One watt is equal to $\frac{1}{746}$ of a horse-power.

It is now possible to understand how to calculate the heat developed in an electrical circuit (see Par. 446).

$$H = 0.24\ C^2\ R\ t. \quad (41)$$

Here H = calories of heat produced; C = current, measured in amperes; R = resistance in ohms, and t = time in seconds.

PROBLEMS.

1. What E. M. F. is needed to maintain a current of 5 amperes in a wire that offers a resistance of 4 ohms?

2. How many amperes will be sent through a resistance of 10 ohms by an E. M. F. of 20 volts?

3. What is the resistance of a wire through which an E. M. F. of 7 volts sends a current of 3 amperes?

4. How many watts are used in a lamp through which a current of 0.5 ampere is sent by an E. M. F. of 110 volts?

5. An incandescent lamp has a resistance of 220 ohms. How much current will be sent through it by an E. M. F. of 110 volts?

6. How many lamps, each of resistance 100 ohms, and using 0.7 ampere, can be lighted by a dynamo having an output of 5000 watts?

7. Given an engine of 40 H. P. so connected with a dynamo that 90 per cent. of its power produces available electrical energy. How many 52-volt lamps could it light if each required one ampere?

8. A wire whose resistance is 5 ohms has a current of 4 amperes sent through it for thirty minutes. How many calories are produced?

9. A resistance of 3 ohms is immersed in 2 liters of water and a current sent through by an E. M. F. of 6 volts. The temperature at first is 5° C. What will be the temperature after one hour?

453. Insulators.—Bare telegraph, telephone, and trolley wires are usually employed in those portions of their circuits that are outside of buildings. In such cases it is necessary to support the conductors on insulators of glass or other non-conducting material. When the wires enter buildings, they are insulated with coverings of rubber, jute, cotton, or other material, either with or without a coating of some insulating wax or resin.

When the E. M. F. is great, as in the case of frictional electric machines, it is necessary to insulate the conductors very carefully. Moisture deposited on the surface of insulators from damp air is a partial conductor of electricity, while dry air, at ordinary pressures, is a non-conductor. All experiments with the electrical charges of high electromotive forces produced by frictional machines should, therefore, be performed in dry, cold weather, since in damp, warm weather an electrified body rapidly loses its charge, owing to the condensation of moisture on the insulating supports.

454. Measurement of Current.—In order to determine the current that is flowing in a conductor any of the effects which the current produces may be used (Par. 440). As a matter of fact, the chemical, thermal, and magnetic effects are all used in measuring instruments.

In a *voltameter* the chemical effect of the current is measured by weighing the cathode on which copper or silver has been deposited from a solution of its salt, or by measuring the volume of the gas evolved when acidulated water is decomposed by the current. The definition of the ampere is based upon a measurement of this kind (Par. 452).

In a hot wire *ammeter* the passage of the current heats a conductor whose expansion is registered by suitable means, or the heat produces a current of electricity by heating one junction of a thermo-couple (Par. 439), and this in turn is measured.

In most instruments it is the magnetic effect of the current which is employed in measurement. In the tangent *galvanometer* (Fig. 243) the current passes in a circular coil of wire around a small magnetic needle placed at the center, in the earth's magnetic meridian. The needle is deflected, and from the amount of the deflection the current is determined. The current is proportional to the tangent of the angle of deflection, not to the angle. For example: if one current gave a deflection of 15°, and another of 30°, the second current would not be twice as great as the other, but in the proportion of the tangents of the angles.

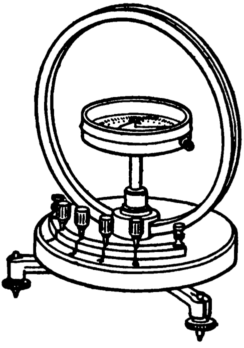


FIG. 243.

Current A. : Current B. = Tang. 15° : Tang. 30°
1 : 2.15 = 0.2679 : 0.5774

455. Astatic Galvanometer.—If two magnetic needles of equal strength are joined so that they point in opposite directions, and if this combination is suspended by unspun silk (Fig. 244), it will have no tendency to set itself in any definite position in the earth's field. It is, therefore, said to be *astatic*. If the instrument is so arranged that the lower needle is in the center of a coil of wire, while the upper needle is above the coil, it becomes very sensitive to small currents. By applying the right-hand rule (Par. 441) it will be found that, of the four possible effects of the current on the two needles, the three strongest all tend to produce rotation of the same kind, while the fourth, the weakest, acts in the opposite direction. The instrument is mounted under a glass cover (Fig. 245) and above a graduated dial.

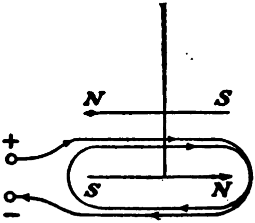


FIG. 244.

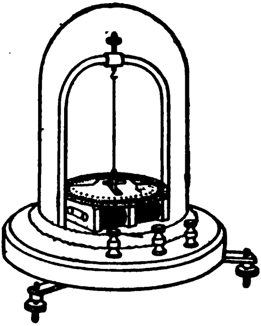


FIG. 245.

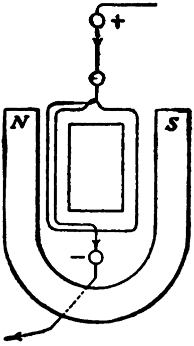


FIG. 246.

456. D'Arsonval Galvanometer.—In this *moving coil* galvanometer, a coil of wire (Fig. 246) is suspended between the poles of a permanent magnet. When the current passes through the coil, it becomes a magnet, and tends to turn so that its N pole will face the S pole of the permanent magnet. A small mirror attached to the suspending wire enables the amount of the current to be read by the deflection of a beam of light to a scale. The complete instrument is shown in Fig. 247.

In other forms of moving coil instruments, as in the Weston, the motion of the coil is controlled by a coiled spring instead of by the suspending wire, and the deflection is read by a pointer and scale.

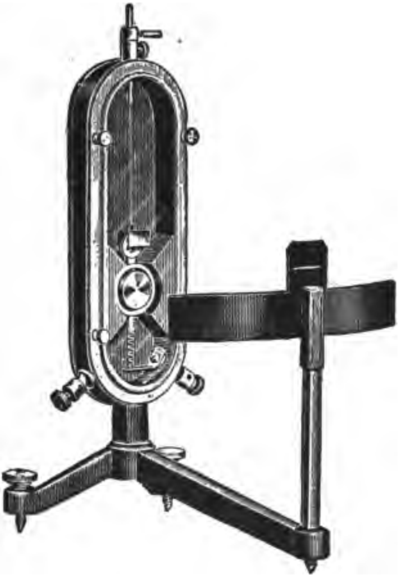


FIG. 247.

457. Ammeters and Voltmeters.—Any form of galvanometer so arranged that its readings are directly in amperes is called an ammeter. Such an instrument is connected in series with any circuit the current of which is to be measured. Its coil has a low resistance.

If the instrument is graduated to read directly in volts, it is called a voltmeter. A voltmeter is used in parallel (shunt) with the circuit whose P. D. is to be measured. Its coil has a high resistance.

458. Resistance Coils.—In order to measure the resistance of a conductor standards are used (Fig. 248) called resistance boxes. These contain coils of wire of varying resistance, the ends of which are connected to metal blocks on the top of the box. In order to prevent the coil acting as a magnet and also to prevent self-induction, each coil of wire is wound with a wire bent on itself, as shown in Fig. 249. The current then has to flow an equal number of times in each direction. When the plugs are in the holes, the current passes through the metal blocks and plugs and meets but a very slight resistance. When a plug is removed, the current must pass through the coil connecting the two blocks. In doing so it meets a resistance the amount of which depends upon the wire. If more than one plug is removed, the total resistance is the sum of that of the coils thrown into action.

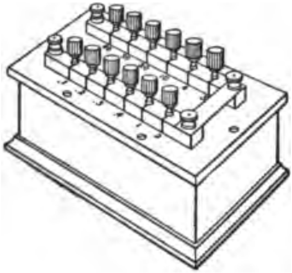


FIG. 248.

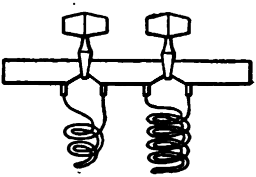


FIG. 249.

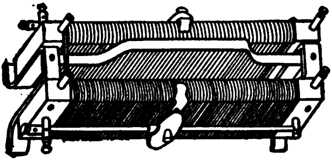


FIG. 250.

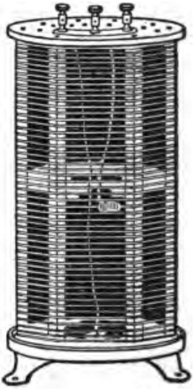


FIG. 251.

In order to adjust the current in a circuit to any desired amount *rheostats* are used. These are arrangements of conductors whose resistance may be adjusted to suit requirements. Two forms of these are shown in Figs. 250 and 251.

459. Voltaic Batteries.—When either the current or the E. M. F. required exceeds that given by a single voltaic cell, a number of cells are connected so as to act together—the arrangement is then called a *battery*.

If the cells are so arranged that the positive terminal of one is connected with the negative terminal of the next (Fig. 252), the cells are said to be in series. In this case the E. M. F. of the combination is equal to the sum of that of the separate cells. The internal resistance of the combination is also the sum of that of the separate cells. If S be used to designate the number of cells arranged in series, and r the internal resistance of a single cell, then Ohm's law for cells in series becomes

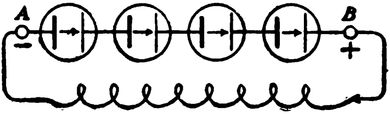


FIG. 252.

$$C = \frac{S E}{R + Sr}. \quad (42)$$

If R, the external resistance, is large, the series arrangement is best for largest current.

If the cells are so arranged that all the positive plates are connected with each other and all the negative plates with each other (Fig. 253), the arrangement is said to be parallel or abreast. In this case the E. M. F. of the com-

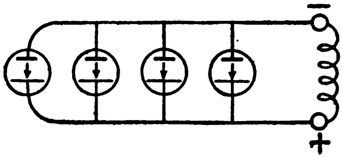


FIG. 253.

bination is the same as that of a single cell, while the internal resistance is less than that of one cell. The formula now becomes—

$$C = \frac{E}{R + \frac{r}{P}}, \quad (43)$$

where P is equal to the number of cells in parallel. If the internal resistance is small, the parallel arrangement is best for largest current.

For some purposes it is desirable to use a combination of the series and parallel methods of grouping. Fig. 254 shows six cells grouped so that two are in series and three in parallel.

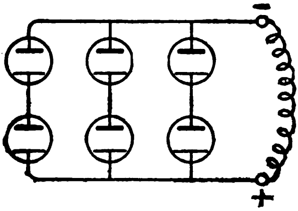


FIG. 254.

The combination of the two formulas above gives for this arrangement

$$C = \frac{SE}{\frac{Sr}{P} + R}. \quad (44)$$

Maximum current will be obtained when $\frac{Sr}{P} = R.$

PROBLEMS

1. How would you arrange 80 cells, each having an E. M. F. of 2 volts and an internal resistance of 3 ohms, so as to send the strongest possible current through a resistance of 2 ohms? How much will the current be?

2. How many cells each of an E. M. F. of 1.5 volts and an internal resistance of 2 ohms will be needed, when arranged in series, to send at least one-half ampere through an external resistance of 50 ohms?

3. Ten cells arranged in parallel, each having a resistance of 8 ohms, produce a current of 0.5 ampere through an internal resistance of 3 ohms. What is the E. M. F. of each cell?

4. What is the greatest resistance through which ten cells, arranged in series, each having a resistance of 1 ohm and an E. M. F. of 2 volts, will send a current of 1 ampere?

5. How can 30 cells, each having an E. M. F. of 1 volt and an internal resistance of 1.5 ohms, be best arranged to send a current through a resistance of 50 ohms? What will the current be?

460. Internal Resistance of a Cell.—If a voltaic cell of some non-polarizing type, as a Daniell cell, is connected with some galvanometer, and the plates are moved nearer to each other or farther from each other, a variation in the reading of the instrument will be noticed. When the plates are completely immersed and as close as they can get, the deflection will be the greatest. When the plates are separated or partly withdrawn from the liquid, the deflection will be less, showing that the current is less. As the E. M. F. of the cell has not changed and the external circuit has remained the same, these changes must have affected the internal resistance of the cell. Ohm's law may be used to express this relation:

$$C=\frac{E}{R+r}.$$

The internal resistance of a cell may be measured by several methods. One method is to connect the cell with an ammeter of very low resistance, using short heavy wires and take the reading of the current. Then introduce a known resistance until the current has become one-half as much. As C has fallen to one-half and E has remained the same, R must have doubled. The amount of resistance thrown into the circuit is, therefore, equal to the internal resistance of the cell.

By means of a voltmeter of high resistance, and an ammeter, the internal resistance of a cell may also be found by what is called the " fall of potential " method.

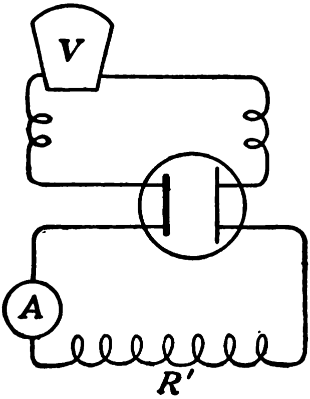


FIG. 255.

Connect the cell in series with the ammeter A (Fig. 255), and an adjustable resistance R', until a moderate current is obtained. Then measure the difference of potential of the terminals of the cell by the voltmeter V.

From Ohm's law, $R = \frac{E}{C} = \frac{V}{A}$.

The internal resistance of the cell is then equal to $R - R'$. It will be found to vary with the amount of current flowing. The internal resistance of a cell is, therefore, not a constant quantity, but varies with the conditions under which it is working.

461. Laws of Resistance.—The resistance of a conductor depends upon its length, cross-section, material, and its temperature.

I. The resistance is directly proportional to the length. If the length of a conductor is doubled, the resistance will be doubled. If it is cut in half, its resistance will be halved.

II. The resistance is inversely proportional to the area of cross-section. A thick wire of twice the area of cross-section of another one of the same length and material will have one-half the resistance. If the *diameter* is made twice as great, the resistance will be one-fourth as much, since areas are proportional to the squares of the diameters.

III. The resistance depends upon the material of which the conductor is made. Iron has a higher resistance than copper.

IV. The resistance of a conductor varies with its temperature. When metals are heated, their resistance increases. If a coil of iron wire is connected to a galvanometer and a current sent through it from some constant source, it will be found that the current decreases when the metal is heated, as by a gas-flame. The resistance of carbon decreases as the temperature increases. In an incandescent lamp the resistance of the hot filament is much less than when it is cold. Certain alloys of manganese, copper, and nickel have a small negative coefficient, that is, their resistance decreases slightly with rise of temperature.

In order to calculate the resistance of a conductor the following formula is employed:

$$R = K\frac{l}{d^2}. \quad (45)$$

Here R = resistance in ohms, l = length in feet, d = diameter in mils (thousandths of a foot), and K = a constant, depending upon the substance taken, being the resistance of one *mil foot*, that is, of a foot of wire having a diameter of one mil.

K at 60° F.

Silver	9.55	Platinum	56.31
Copper	9.82	Iron	62.62
Gold	12.98	Lead	124.77
Zinc	35.46	German silver	185.11

462. Specific Resistance.—By specific resistance or resistivity is meant the resistance in ohms of a piece of the substance 1 cm. long and having a cross-section of one square cm., that is, the resistance between the two opposite faces of a centimeter cube of that substance.

The formula for the resistance of a conductor may also be expressed in this form:

$$R = r\frac{l}{A}. \quad (46)$$

Where l = length in centimeters.
A = area in sq. cm.
r = specific resistance.
R = ohms.

Specific resistance at 0° C., from Smithsonian Tables:

Aluminum	2.906×10^{-6} ohms.
German silver	20.89×10^{-6} ohms.
Copper, annealed	1.584×10^{-6} ohms.
Iron, annealed	9.693×10^{-6} ohms.
Silver	$1.56, \times 10^{-6}$ ohms.

$$\left(10^{-6} = \frac{1}{10^6} = \frac{1}{1,000,000} = 0.000001\right).$$

PROBLEMS

1. A wire 20 ft. long has a diameter of 0.05 in. What must be the diameter of a wire 50 ft. long to offer (*a*) the same resistance? (*b*) one-half as much resistance?

2. Find the resistance of a mile of copper wire having a diameter of 0.0655 inch.

3. What is the diameter of a piece of iron wire 50 miles of which offers a resistance of 500 ohms?

4. What will be the length of a piece of silver wire having a diameter of 0.055 in. and a resistance of 10 ohms?

5. What will be the resistance of 40 m. of silver wire whose diameter is 3 mm.?

6. Find the resistance of a copper conductor 1 sq. cm. in cross-section, long enough to reach from Niagara to New York—480 kilometers.

463. Joint Resistance of Conductors.—When any number of conductors are arranged in series, the combined resistance is equal to the sum of the resistances of the separate conductors. If a current is sent through three wires joined in series, whose separate resistances are respectively 1, 2, and 3 ohms, it will meet with a resistance of 6 ohms.

When conductors are joined in parallel, the combined resistance is less than that of any conductor by itself; for now the current has more than one path in which it can flow. The reciprocal of the combined resistance is equal to the sum of the reciprocals of the resistances taken separately. If r_1, r_2, and r_3 are three resistances joined in parallel, then the combined resistance R is found from the equation—

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}. \quad (47)$$

If there are but two conductors joined in parallel, then—

$$R = \frac{r_1 r_2}{r_1 + r_2}. \quad (48)$$

Figure 256 represents three conductors joined in series. Their combined resistance is their sum, 6 ohms.

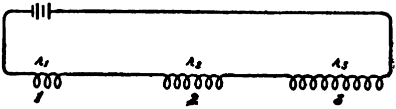


FIG. 256.

Figure 257 represents the same three conductors joined in parallel.

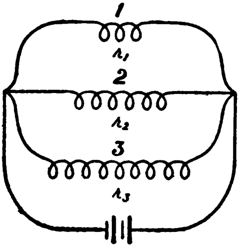


FIG. 257.

$$\frac{1}{R} = \frac{1}{1} + \frac{1}{2} + \frac{1}{3} = \frac{11}{6}.$$

$$R = 1\tfrac{5}{6} \text{ ohms.}$$

PROBLEMS

1. Two wires, having resistances of 25 and 50 ohms respectively, are joined in parallel (or multiple arc). Find their combined resistance.

2. Three wires, each having a resistance of 3 ohms, are joined in series. How many times greater is their combined resistance than if they had been joined in parallel?

3. If the resistance of a conductor connecting two points is 50 ohms, what must be the resistance of an additional conductor connecting these points in order that the combined resistance may fall to 40 ohms?

4. When a 110 V. incandescent lamp is lighted, it has a resistance of 220 ohms. If 5 such lamps are in parallel, find their combined resistance.

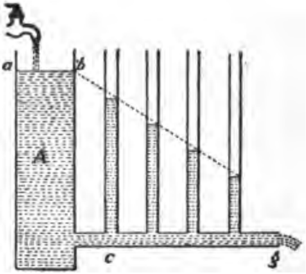


FIG. 258.

464. Fall of Potential.—If a vessel *A* (Fig. 258) be filled with water to the level *a–b* and this level be maintained constant while water flows out the pipe *c–g*, the pressure in the different parts of the pipe *c–g* will fall from the point *c* to the point *g*. This pressure may be measured by means of tubes opening into the pipe, the height of the water measuring the amount of the pressure. The height of water in the vessel *A* is sufficient to overcome the resistance of all the pipe. The height in the tube *c* is sufficient to overcome the resistance of that part of the pipe from *c* to *g*. As the resistance is overcome, the pressure falls. The current of water in all parts of the pipe remains the same if the pressure is kept constant. In terms of Ohm's law this may be expressed by saying that if C is kept constant, any variation in R is accompanied by a corresponding variation in E, so that their ratio, $\frac{E}{R}$, remains the same. *The fall of potential along a conductor is, therefore, proportional to the resistance overcome.*

PROBLEMS

1. The fall of potential through a set of resistance coils is 600 volts. If the current is 15 amperes, what is the resistance of the coils?

2. What is the strength of a current which, falling 12 volts, yields 0.005 horse power?

3. A difference of potential of 4.5 volts is maintained at the terminals of a wire of 0.2 ohm resistance. What current flows?

4. The resistance between two points in a circuit is 15 ohms. An ammeter shows that there is a current in the circuit of 1.5 amperes; what is the difference in potential between the points?

465. Wheatstone Bridge.—A method of finding the resistance of a conductor which is of very wide application is based on the principle of the fall of potential, just discussed, and is known as the Wheatstone bridge. Let the current from a battery divide at the point A (Fig. 259), part going by the path $A\ X\ B$, and part by the path $A\ \ Y\ B$, the two currents uniting again at B. As the potential in both circuits is the same at A, and again the same at B, the fall of potential in each branch must have been the same. For any point Y in the lower circuit there must, therefore, be some point in the upper circuit which has the same potential. Let this be X. If these two points are joined by a conductor, no current will flow, as indicated by a galvanometer, G. The point X may, therefore, be found by exploring until, on closing the circuit, there is no deflection of the galvanometer. In the circuit *A X B*, since *C* is the same in all its parts, $R_1 : R_2 ::$ Fall of potential from *A* to *X* : Fall of potential from *X* to *B*. In the circuit *A Y B*, for the same reason, $R_3 : R_4 ::$ Fall of potential from *A* to *Y* : Fall of potential from *Y* to *B*. But,

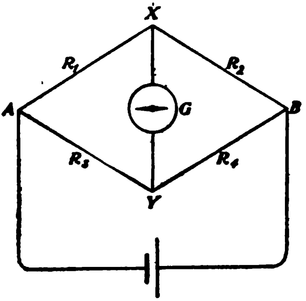


FIG. 259.

since *X* and *Y* are at the same potential, the fall of potential from *A* to *X* = the fall of potential from *A* to *Y*; and also the fall of potential from *X* to *B* = fall from *Y* to *B*.

$$\text{Therefore, } R_1 : R_2 :: R_3 : R_4.$$

In practice two of these resistances are found by the relative lengths of a stretched wire of uniform diameter, and a third is that of a known rheostat, so that the fourth, the desired unknown, is easily found by calculation.

PROBLEMS

1. In a measurement with a slide wire bridge "balance" was obtained with the slider at 48.55 cm., and the resistance box on the same side of the bridge, reading 17.6 ohms. What was the unknown resistance?

2. In a slide wire bridge "balance" was at 49.25, with the resistance box on that side reading 54.2 ohms. When the resistances were reversed, the "balance" was at 50.65 when the box read 54.6. Find the correct value of the unknown resistance.

CHAPTER XXVII

ELECTROMAGNETIC INDUCTION

466. Mutual Action of Currents.—We have found that suspended magnets have a mutual action upon each other. We have found that a conductor in which a current is flowing has a magnetic field surrounding it, and exerts a directive force upon a magnetic needle. It is not, therefore, surprising to find that currents have a mutual action.

Experiment 126.—Pass a current through two parallel wires, so that it flows in the same direction in both. The wires will move toward each other if they have freedom of motion. In the apparatus pictured in Fig. 260 the wires dip in a cup of mercury and they are suspended so that they can swing freely.

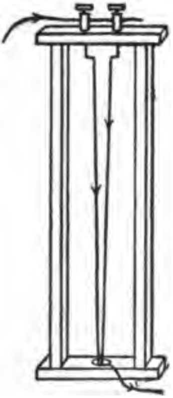


FIG. 260.

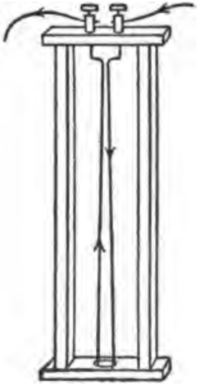


FIG. 261.

First Law of Currents.—Parallel currents flowing in the same direction attract each other.

Experiment 127.—Arrange the same apparatus as shown in Fig. 261 so that the current flows down one wire and up the other. The wires will move away from each other.

Second Law of Currents.—Parallel currents flowing in opposite directions repel each other.

The first law of currents is also nicely illustrated by the following experiment:

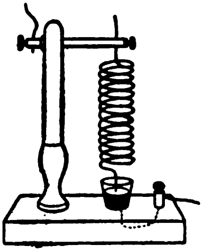


FIG. 262.

Experiment 128.—Suspend a coil ot wire in a frame (Fig. 262) so that the upper end can be connected to a circuit and so that its lower end just dips into a mercury cup, the other side of which is also connected to the same circuit. When the circuit is closed, the coil will be shortened so that the mercury contact is broken. This breaks the circuit, the attraction of the parallel currents for each other ceases, and it again touches the mercury, only to repeat the operation.

467. Induced Electro-motive Force.—

Experiment 129.—Connect a coil of wire to a sensitive galvanometer and thrust a bar magnet through one end of the coil. A momentary movement of the needle shows that a current passed in the coil. Remove the magnet, and the galvanometer shows that a current passed in the opposite direction. Reverse the magnet and thrust it into the coil and a current will flow like that produced when the other end was withdrawn. Now withdraw the magnet and the current flows as it did at first.

A current produced this way is called an induced current. *Whenever the number of lines of force passing through a closed conductor is caused to vary, an induced current flows in the conductor.* The E. M. F. which causes the current is called an induced E. M. F.

Experiment 130.—Arrange a set of apparatus as shown in Fig. 263. A hollow coil A, called the *primary coil,* of moderately stout insulated wire, is connected by wires a, b, c, d, with a voltaic cell C. Another hollow coil B, called the *secondary coil,* formed of a considerable length of insulated wire, surrounds the primary coil. The ends of this coil are connected by means of the wires *e* and *f*, to a galvanometer *G*.

If the primary coil *A* is pushed into or withdrawn from the coil *B*, the motion of the galvanometer needle will show that an induced current is formed. This, of course, is only a special case of the general law as given in the previous paragraph. Around the primary coil there is a field of force, just as there is around the bar magnet.

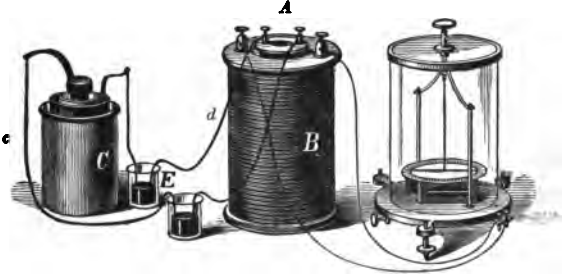


FIG. 263.

If the binding posts of the galvanometer are so marked that the direction of motion of the needle tells which way the current is flowing in the coil, the last experiment can also be used to prove Lenz's law. If the end of the primary coil *A*, in which the current is flowing clockwise, that is, the *S* pole, is thrust into the coil *B*, the induced current will so flow that it makes this end of *B* also an *S* pole. Between the like poles there is, therefore, a repulsion, and work must be done in forcing the poles together. When *A* is withdrawn, the current in *B* makes an *N* pole of this end, which tends to attract *A*, and work must be done in pulling the coils apart. Hence, Lenz's law may be stated this way: *The induced current always flows in such a way as to oppose the motion of the inducing agent.* With a bar magnet the same law will be found to hold.

If one of the wires conveying the electric current as *d*, be raised from the mercury in the cup *E*, so as to break the circuit, and thus cause the electricity to stop flowing through the primary coil, a momentary current will at once be induced in the secondary coil, as will be shown by the movement of the needle of the galvanometer in a certain direction. After a few moments the needle will come to rest, thus showing that the current in the secondary coil has ceased to flow. If, now, the wire *d* be again placed in the mercury cup, so that a current from the battery may flow through the primary coil, the galvanometer needle will again be deflected, but in the opposite direction to that produced by the breaking of the circuit of the primary coil, thus showing that the induced current produced in the secondary coil, by closing the primary circuit, is in the opposite direction to that produced by opening the primary circuit.

468. Methods of Obtaining Induced E. M. F.—Three methods have just been described for obtaining an induced current, all being special examples of the general method—cutting lines of force by a closed conductor. The first method, in which the lines of force of a permanent magnet are cut by a closed conductor, is used in the magneto. The second method, in which the lines of force of an electromagnet are cut by a conductor is used in the dynamo. The third method in which the coil remains unmoved, while the current is made or broken in the primary, is used in the induction coil.

469. Intensity of Induced E. M. F.—If, in Experiment 129, the bar magnet is moved more rapidly, the current produced is greater. If it is replaced by a stronger magnet, the current is also greater. If a stronger current is sent through the electromagnet *A*, in Experiment 130, a higher E. M. F. is produced. The *strength* of the induced E. M. F. depends upon the *rate* at which the lines of force are cut. Hence, any increase in the strength of the magnetic field, in the number of turns of wire of the conductor, or in the speed of the motion, will increase the induced E. M. F.

470. Self-induction.—

Experiment 131.—Connect two cells of a storage battery with a long coil of wire. When the circuit is broken, a spark will pass. When the circuit is made, no spark will be noticed. This spark is sometimes said to be due to the *extra current*. This is an example of *self-induction*.

Not only is an induced current formed in a secondary coil, by the making and breaking of the current in the primary, but, as shown by the above experiment, the making and breaking of the current induce a current in the turns of the same coil. Applying Lenz's law, we can see why the current at break is so much more than the current at make. At make the induced current hinders the flow of current and prevents its rising immediately to its full value. At break the induced current prolongs the current, and hence they both flow in the same direction. In other words, the electricity in a wire possesses inertia, and, therefore, cannot be started or stopped instantly.

471. The Induction Coil.—The induction coil, as shown in the diagram (Fig. 264), consists essentially of a coil containing a core of soft iron wires, a secondary coil, some form of breaker, and a condenser. As shown in the drawing, the current breaker, or interrupter, is of the electromagnetic type. When the key at *K* is closed, the current flows in the primary coil, which is of comparatively few turns of thick wire. This makes the iron core a magnet, and the armature is attracted, thus breaking the current at *R*. When the current is broken, the electromagnet ceases to act, and the spring of the armature, therefore, carries

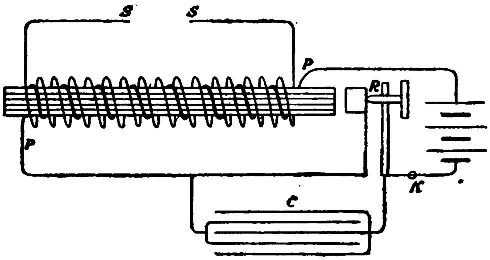


FIG. 264.—Section of induction coil.

it back until the circuit is closed, when the action continues as before.

When the primary circuit is closed, an induced E. M. F. is produced in the secondary coil, which is of many turns of fine wire. This induced E. M. F. is in the opposite direction to that of the primary. When the current in the primary is broken, the induced E. M. F. in the secondary is now in the same direction as that of the primary. The object of the induction coil is to transform the low E. M. F. of the battery into a very much higher E. M. F. It is, therefore, a step-up transformer.

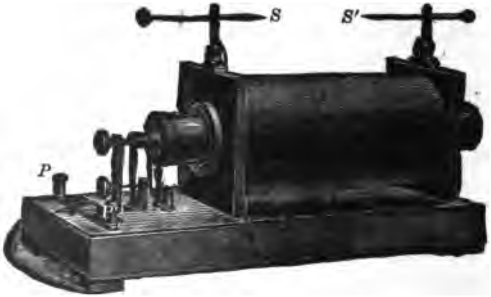


FIG. 265.—Ruhmkorff induction coil.

We have seen that the E. M. F. depends upon the rate at which lines of force are cut. It is to increase this rate that a condenser is introduced. When the current in the primary is broken, the self-induced current tends to prolong the time of break by sparking across the gap. The condenser absorbs this extra current, and so makes the time of break more nearly instantaneous.

The secondary current which streams from the terminals of the coil is mainly in one direction. This is due to the fact that the condenser, by decreasing the time of break, increases the rate of variation of the magnetic field. Since the E. M. F. is proportional to the rate of variation of the magnetic field, the E. M. F. at break is, therefore, greater than at make.

Induction coils are necessary in telephony and in wireless telegraphy, as will be explained later. By means of them very beautiful effects can be obtained with tubes containing air and other gases under reduced pressure. This will be discussed under the topic of radiation.

472. The Simple Dynamo.—We have found when a bar magnet is thrust into or withdrawn from a coil of wire connected with a galvanometer, that a current is generated in the coil. It is this principle which is employed in the dynamo, now so largely used for producing electric currents. In order to study the machine more carefully, we will reverse the moving parts and think of the coil of wire as moving between the poles of a magnet.

Let *N* and *S* (Fig. 266) represent the two pole pieces of a magnet. The lines of force, as indicated, go from *N* to *S*. If a loop of wire is inserted in the field, as shown, and rotated clockwise, a current will be generated in the wire loop, tending to oppose the motion. To predict which way the induced current will flow it is necessary to remember that lines of force which have a common direction oppose each other (see Fig. 204), and also the method of predicting the direction of the circular lines of force surrounding a current flowing in a conductor (Par. 441).

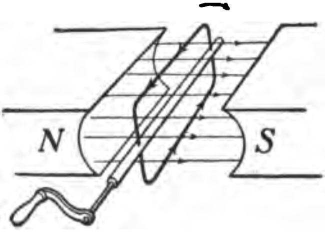


FIG. 266.

These two rules may be combined as follows: If, while looking along the lines of force, a conductor is dropped so as to cut them at right angles, the induced current will flow to the right.

As the diagram (Fig. 267) shows, the circular lines of force are in the same direction as those of the field, and, therefore, oppose the motion. In overcoming this opposition energy is, therefore, expended and produces the flow of current.

At a position of 90° in advance of this, when the plane of the coil is horizontal, the rate of cutting lines is greatest, and, therefore, the E. M. F. is the greatest. As it advances through the second quarter revolution the E. M. F. falls to zero. As it now completes the first half revolution the direction of the induced current changes, for it is now cutting the lines of force of the field in the opposite direction. If the current is taken off by means of brushes touching metal rings to which the ends of the wire are fastened, this current, in one revolution of the loop, will have two minima and two maxima, and will flow for one-half the revolution in one direction and for one-half the revolution in the opposite direction. Such a current is known as an alternating current, often spoken of as A. C.

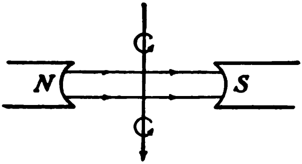


FIG. 267.

473. The Commutator.—For many purposes, as, for example, electroplating, it is necessary to have some device by which the alternating current can be made a direct one, that is, so that it may always flow in the same direction. This purpose is accomplished by means of an arrangement called a *commutator* (Fig. 268). Instead of fastening the end of the coil of wire to a ring of metal so that current flows to or from the brush during the whole of the revolution, the wire is fastened to a bar of metal insulated in such a way that current is allowed to flow from or to it only at a certain point. This point is chosen so that at one brush the current always flows out, while at the other brush it always flows in. In the outside circuit connecting the

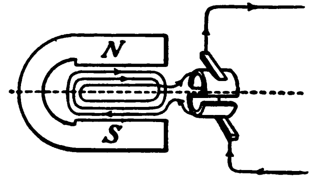


FIG. 268.

two brushes the current is, therefore, a direct one, that is, D. C. In practice the revolving piece, called the armature, is made up of many loops of wire, so that in a single revolution there are many conductors cutting the field of force. The commutator (Fig. 269) is, therefore, made up of many insulated segments opposite bars being connected to opposite ends of loops.

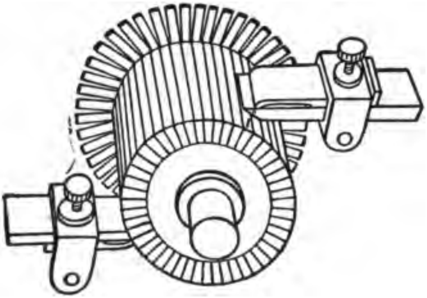


FIG. 269.

474. The Magneto.—If the dynamo is constructed as just explained, having the field of force produced by a permanent magnet, it is called a *magneto*. Such an instrument is used for supplying a current to fire a mine at a distance, for the ignition of a gasolene engine, and that form of telephone for which the ringing current is not supplied from the central station. As the strength of field is limited to that which the permanent magnet can supply, the use of the magneto is restricted, as it can produce but a small current. For greater E. M. F. another device must be used.

475. The Dynamo.—In the dynamo proper the field of force is supplied by an electromagnet. At the beginning of the motion there is a weak field, due to residual magnetism. The small amount of current produced is sent around the field magnet. This creates a stronger field, and so, in a short time, the field is " built up " to the limit of the magnetization possible. There are three general ways in which field magnets are wound.

476. Various Windings.—*Series-winding.*—In the series-wound dynamo (Fig. 270) all the current produced goes around the field magnets. Such a dynamo is used in lighting arc lamps in series. If the external resistance is varied, the E. M. F. changes to suit the conditions.

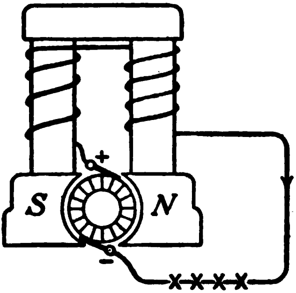


FIG. 270.—Series-wound dynamo.

Shunt-winding.—In the shunt-wound dynamo (Fig. 271) there are two circuits through which the current flows. One of these energizes the field. The other one, entirely separate, supplies the outside energy, as for lighting incandescent lamps. If more resistance is thrown into the outer circuit, more current flows in the field coils and the E. M. F. rises.

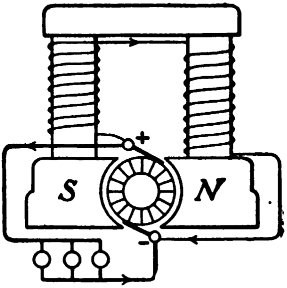


FIG. 271.—Shunt-winding.

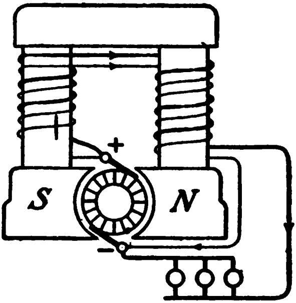


FIG. 272.—Compound-winding.

Compound-winding.—In the compound-wound dynamo (Fig. 272) both coils go around the field. One of the coils also goes to the outside circuit. In such a dynamo the E. M. F. may be kept at a constant value, and this type is especially useful for lighting incandescent lamps, where any change in voltage would affect the candle power.

477. The Alternator.—For many purposes it is desirable to employ an alternating current. This is particularly the case where power is to be transmitted a considerable distance. In such a condition, if it is sent under a high E. M. F., the current strength may be low, so that a conductor of small cross-section, and consequently light weight and small cost, may be used.

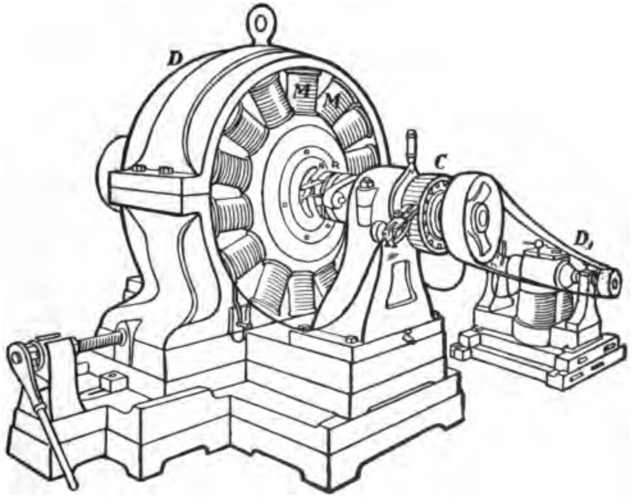


FIG. 273.

The alternating current produced may be raised to a higher E. M. F. by means of a step-up transformer. At the place where the current is to be used a step-down transformer may be employed, and any desired E. M. F. obtained.

As the field of the alternator, *D* (Fig. 273), could not be maintained by its own alternating current, the direct current needed is supplied by a small outside direct-current machine, *D'*, called the *exciter*.

In order to regulate automatically the pressure under all loads the field magnets of some alternators have two circuits. The outside direct current generator excites one of these circuits, while the other circuit is excited by a portion of the alternating current supplied by the machine, this being made direct by the commutator *C*. The alternating current for the external circuit is obtained from the rings *R*. *R*.

478. The Transformer.—The induction coil has been spoken of as a step-up transformer (Par. 471). If the windings are reversed so that the primary has more turns than the secondary, it becomes a step-down transformer. In Fig. 274 the core of iron wire has two coils of wire wound upon it. If one has ten times as many turns as the other, an alternating current of 1100 volts sent through one, will produce an induced E. M. F. of 110 volts in the coil of fewer turns. The transformer is frequently located at the spot where the low-tension current is to

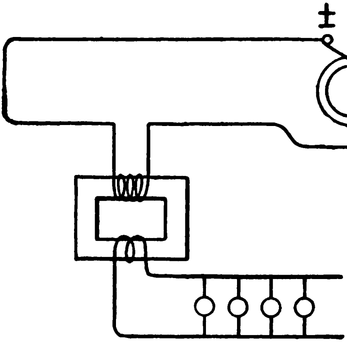


FIG. 274.

be employed, as just outside a house where incandescent lamps are used.

479. The Electric Motor.—If instead of driving the armature of the dynamo by mechanical force, a continuous electric current be passed through the circuit, the armature will revolve and develop mechanical power. The dynamo then becomes an *electric motor*, a device by means of which electric energy is transformed into mechanical energy.

The cause of the rotation of the electric motor is the mutual action which the magnetic flux of the armature and of the field magnets exert on each other.

Electric motors are of a great variety of forms. They can be operated both by direct and by alternating electric currents. The form of motor shown in Fig. 275 is operated by direct or continuous currents.

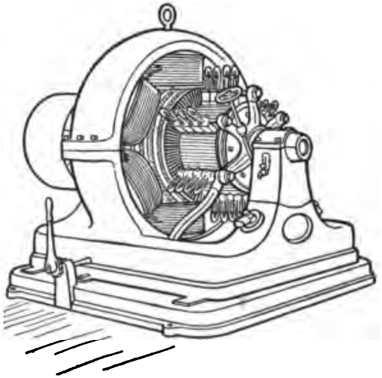


FIG. 275.

480. Action of a Direct Current Motor.—The action of a motor is most readily explained by reference to the moving coil galvanometer described in Par. 456. If the direction of the current is reversed just as the inertia of the coil has carried it past the point where the lines of force are parallel to those of the field, it will continue to turn if there is no torsion to prevent it. In the motor the reversal of the current is produced by the commutator, and as the armature works in bearings there is no torsion to prevent its motion.

CHAPTER XXVIII

APPLICATIONS OF ELECTRICITY

481. Arc Lamp.—The voltaic arc has already been referred to as an example of the heating effects of the current. The light of the voltaic arc is of dazzling brightness, and the arc itself is the most intense source of heat that can be produced artificially.

While the carbon electrodes are separated from each other, portions of the positive electrode, volatilized by the intense heat, are carried, in the form of an arc or bow, through the air, to the negative electrode, on which a part is condensed in the form of graphite. Both carbons decrease in size, the positive carbon decreasing more rapidly than the negative.

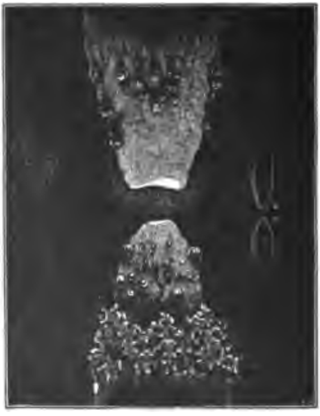


FIG. 276.

Fig. 276 shows a magnified image of the carbon electrodes, obtained by means of a suitable lens placed in front of them. The image so formed is received on a distant screen. A tiny crater or hollow may be observed in the end of the positive carbon. A tiny nipple or projection is formed on the opposing surface of the negative carbon. The intense heat of the arc changes the hard carbon of the electrode into a soft variety of carbon called graphite, the material employed in lead-pencils.

The intense brilliancy of the electric arc-light renders it admirably adapted for the illumination of light-houses, for large buildings, for the streets of cities, or for large areas generally.

The consumption of the carbon electrodes by combustion, and the growth of the negative carbon at the expense of the positive, render it necessary to employ some means by which the carbons may be maintained a constant distance apart; for, if they should get too far apart, the current at once ceases and the light goes out, in which case the carbons must be brought together again, and slowly separated before the light reappears. The carbons are kept at a suitable distance apart by various forms of *electric arc lamp mechanism.*

482. Arc-lamp Control.—One form of arc-lamp control is shown in Fig. 277. The current divides at X, the main line passing around the electromagnet in series with the arc. The shunt circuit is wound around the same core, but in the opposite direction. When the carbons are in contact and the circuit is completed, the electromagnet pulls the clutch up which separates the carbons and "strikes the arc." As the carbons burn away, the arc increases in length, the resistance of the series circuit increases, and more current passes to the shunt. As this field is opposite to that of the series, the clutch is released and the arc is shortened. The two windings of the electromagnet are so adjusted that the arc is maintained at a practically constant length.

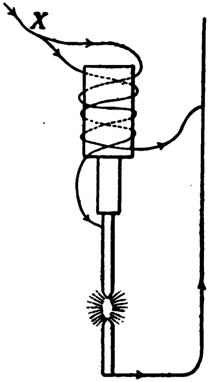


FIG. 277.

The ordinary open arc lamp usually requires 10 amperes and a P. D. of 50 volts. It, therefore, consumes 500 watts. If its mean spherical candle power is taken as 500, this means that 1 watt is required per candle power.

Arc lamps are usually connected in series. If 100 lamps are to be run by one dynamo, it will have to produce an E. M. F. of 50 × 100 = 5000 volts.

In the enclosed arc lamp, a closely fitting glass globe surrounds the carbons. By this means an atmosphere free from oxygen is maintained, so the carbons burn up much less rapidly.

Recently it has been found that the core of the carbon can be made of substances having greater power of giving light than carbon. Such lamps, whose carbons contain lime, magnesia, silica, or some other such compound, are called flaming arcs. Their efficiency is very great, sometimes as high as about 4 candles per watt.

483. Incandescent-lamp Illumination.—Arc lamps give so great a quantity of light that for inside lighting, such as in an ordinary room, a single lamp is more than sufficient. A single source of light, however, is apt to produce marked shadows. It is, therefore, preferable to employ a number of less powerful lights, so that each light may illumine the space occupied by the shadow of some other light, and thus produce a more nearly uniform illumination. This is effected in practice by the use of the incandescent lamp.

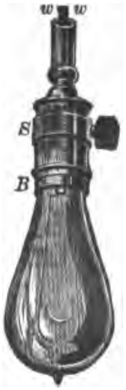


Fig. 278.

The *incandescent lamp* derives its light from the glowing of a fine thread or filament of carbon, that is rendered incandescent by the passage of an electric current through it. Since carbon readily burns in the air, it is necessary to place the carbon inside an exhausted glass chamber from which practically all the air has been removed. The carbon filament is obtained from a carbonaceous paste that is pressed or squirted through a die plate and then carbonized.

A form of incandescent electric lamp is shown in Fig. 278. The carbon filament is mounted inside the lamp chamber on a support through which pass the leading-in wires that lead the current into the lamp chamber. The ends of these wires are so electrically connected respectively to the two pieces of metal in the base *B* of the lamp, that the mere insertion of the *lamp-base* into the *lamp-socket* *S* connects the lamp with the wires *w*, *w*, from which the current is obtained.

484. Incandescent Lamps.—Incandescent lamps are usually connected in parallel between the supply mains. They are usually lighted by a 110-volt circuit, and require about 0.5 of an ampere. Such a lamp, if of 16 candle power and using 55 watts, will have an efficiency of about 3.5 watts per candle power.

If the voltage of the circuit is higher than 110 volts, the lamps are often arranged in series to meet the conditions. On a trolley circuit, where a 550-volt circuit is often used, five lamps are, therefore, put in series.

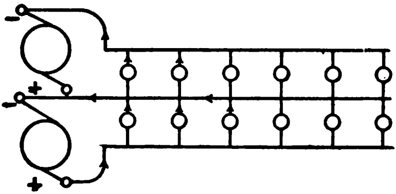


FIG. 279.

In the Edison three-wire system two dynamos are joined in series, and the circuit consists of three wires, as shown in Fig. 279. If the same number of lamps are lighted in each circuit, no current flows in the middle wire, but if more lamps are lighted on one side than on the other, the extra current flows through the middle wire. By this arrangement the lamps all burn with equal candle power, and the wire required for the total circuit is much reduced.

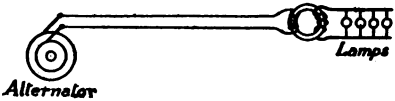


FIG. 280.

Fig. 280 shows how a system of lamps is lighted by means of a transformer, which obtains its alternating current under high pressure from an alternator.

Recently it has been found that certain metals whose melting points are very high can be used to replace the carbon filament. Tantalum, osmium, and tungsten have all been used. Fig. 281 shows a tungsten lamp. It will be noticed that on account of its much greater conductivity a longer filament must be employed. This is supported as shown in the cut. The light given by the lamp is very pleasing and its efficiency is very high—about 1 to $1\frac{1}{4}$ watts per candle power.

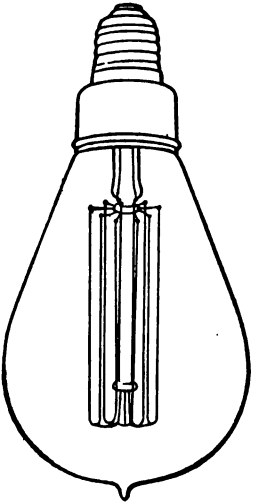


FIG. 281.

485. The Uses of the Electromagnet in Signaling Apparatus.—The rapidity with which an electromagnet acquires and loses its magnetism, on the making or breaking of the electric circuit in which it is placed, is utilized in a great variety of signaling apparatus. In all these the signals are produced by the to-and-fro movements of the armature of an electromagnet, which produces audible sounds, rings bells, moves needles, or operates visual signals generally. Among the most important of such signaling apparatus are the telegraph, the electromagnetic annunciator, the electric burglar alarm, and call apparatus generally.

486. The Electric Telegraph.—In the electric telegraph, electromagnets are employed to transmit intelligence, by the movements of their armatures, on the opening and closing of their circuits, either by means of the movements of a needle over a dial plate, or by the recording of certain arbitrary characters in the form of dots and dashes that represent the letters of the alphabet; or, more commonly in the United States, by means of certain sounds which stand for or represent the letters of the alphabet.

In all systems of telegraphy a *line wire* or conductor connects the two stations between which it is desired to establish communication. At each station a device called a *telegraphic key* is provided, for readily making or breaking the circuit, together with some form of *receiving apparatus* containing an electromagnet, either for recording or for rendering visible or audible the signals received.

487. The Morse Alphabet.—In the following table are given the combinations of dots and dashes employed in the Morse system to represent the letters of the alphabet and the numerals.

a - —
b — - - -
c - - -
d — - -
e -
f - — -
g — — -
h - - - -
i - -
j — - — -
k — - —
l ——
m — —
n — -
o - -
p - - - - -
q - - — -
r - - -
s - - -
t —
u - - —
v - - - —
w - — —
x - — - -
y - - - -
z - - - -
& - - - -
1 - — - - -
2 - - — - -
3 - - - — -
4 - - - - —
5 — — —
6 - - - - - -
7 — — - -
8 — - - - -
9 — - - —
0 ——

488. The Morse Sounder.—Originally, the Morse receiving telegraphic instrument was an electromagnetic register, which recorded, in the form of dots and dashes, the signals sent over the line on a band of paper. It was found in practice that the operator soon learned to receive the telegraphic message by sound, even more readily than by means of the recorded dots and dashes received on the moving band of paper. This led to the general introduction of a form of receiving instrument called the *telegraphic sounder*. A form of Morse sounder, together with a key generally employed in Morse telegraphy, is shown in Fig. 282. The movements of the armature *A*, of the electromagnet *M*, cause a lever *L*, connected therewith, to produce a series of clicks or sounds as it strikes against front and back stops placed in the support *B*. *K* is the key handle or knob. A switch, *S*, is provided for cutting the key out of the circuit when so desired.

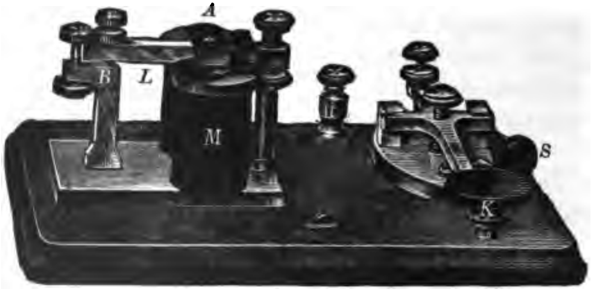


FIG. 282.

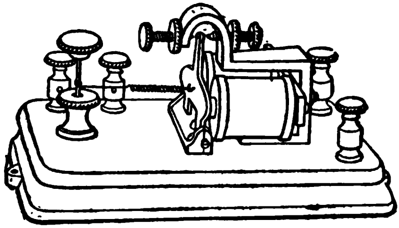


FIG. 283.

489. The Telegraphic Relay.—In long telegraphic lines, when the current reaches the distant end of the line, it is too weak to produce an audible signal or to form a satisfactory record. In such cases a form of apparatus is employed called a *telegraphic relay* (Fig. 283), consisting of an electromagnet whose magnetizing coil contains many turns of fine wire. The armature of the relay magnet is employed to open and close the circuit of a local battery, the current of which operates either the sounder or the recording apparatus. By means of the relay it is possible to send telegraphic dispatches across an entire continent.

The electromagnet is connected in series with the main line. When the armature is attracted, it closes a gap in the local circuit so that the local batteries can act, and thus the sounder makes audible the message, which otherwise could not be heard.

490. The Telegraphic Circuit.—Fig. 284 shows the general arrangement of the relay in a telegraphic circuit. When the current comes through the relay *R*, it attracts the armature and closes the gap *A*. This enables the local battery to act and the sounder *S* respond.

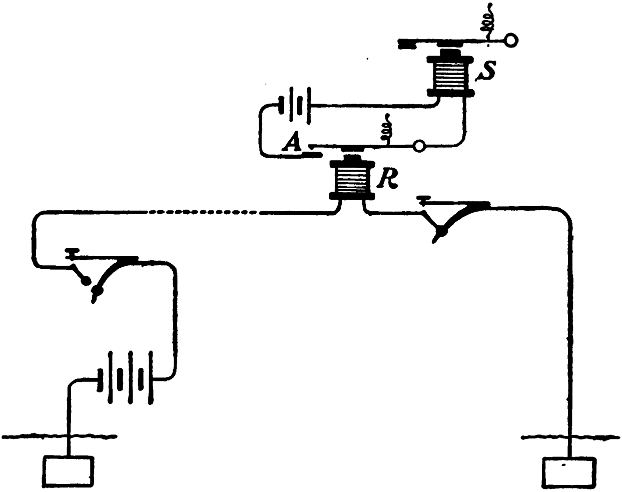


FIG. 284.

The return circuit is completed through the earth, as shown by the plate. This affords the advantage of using a return conductor of no cost and of practically no resistance.

491. The Electric Telephone is an instrument by means of which the sounds of the human voice, as in articulate speech, uttered in any place, can be audibly reproduced at places even hundreds of miles distant. The telephone consists of a transmitting and receiving instrument connected by a line wire or conductor. One of the simplest forms of telephone is shown in Fig. 285. Here the same form of transmitting and receiving instrument is employed at each end of the line. A permanent magnet, provided with a coil of insulated wire wrapped around it near one end, is connected at one of its ends to a wire *E L*, which passes to a distant station, where it is connected to one end of a similar coil wrapped around a permanent magnet. The other ends of the coils are either connected by means of wire *A B H*, or, what serves the same purpose, are connected to metallic plates buried in the earth at *A* and *H*. The circuit so provided is called a *telephone circuit.* The apparent break in the wire *E L*, at *a*, is intended to represent a great length of wire.

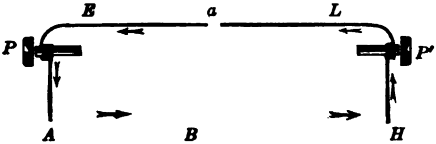


FIG. 285.

The method of operation of the instrument is as follows: a circular diaphragm of thin sheet iron is fastened at its edges to a mouth-piece, *P*, of wood. On speaking into this mouthpiece the diaphragm is moved in and out by the sound-waves. The soft-iron diaphragm being near the magnet becomes a magnet by induction, and as it is moved toward and from the magnet by sound-waves, it produces induced E. M. F.'s and currents in the coil of wire, by causing its flux to pass into and out of the coil of wire. These currents, traversing the circuit, flow through the coil at the distant station, and, by changing the strength of the magnet there, cause the diaphragm at *P'* to pass through movements precisely similar to those produced by the sound-waves at *P*. An ear, therefore, placed at *P'*, will hear all that is said at *P*. One may even recognize the peculiarities of the distant speaker's voice.

The manner in which the currents, flowing through the coil at *P'*, cause movements in its diaphragm may be readily understood by considering a single motion of the diaphragm at *P*, toward and from its magnet. Suppose that, by moving it *toward* the magnet it causes an electric current which traverses the telephone circuit and flows through the coil at *P'*, so as to strengthen the magnet: the diaphragm at *P'* is at once drawn nearer to its magnet. When now the diaphragm at *P* moves away from its magnet, it produces a current of electricity in the opposite direction to that produced by its first movement, which current, flowing through the coil at *P'*, weakens the magnet, when the elasticity of the diaphragm at *P'* causes it at once to move away from its magnet.

Since these movements of the diaphragm correspond precisely to the movements of the sound-waves, it will be seen that the diaphragm at *P'*, is moved in precisely the same manner as the diaphragm of a person's ear would be if he were near the speaker. A person listening at *P'* should, therefore, be able to hear all that is spoken at *P*.

The magneto-electric telephone, when used as a transmitter, is in reality a dynamo operated by the voice. The sound-waves striking the diaphragm produce electric currents which flow through the telephone circuit. When used as a receiver, the telephone acts as a motor, for these electric currents reproduce in a distant diaphragm the exact movements of the first. Electric currents and not sound-waves pass through the wire connecting the telephones.

The construction of the magneto-telephone will be better understood by an inspection of Fig. 286, which represents a section of the instrument. The magnet, *H F*, has a coil, *C*, at one of its ends, the ends of the coil being connected to binding screws at *x* and *y*. The diaphragm *D* is placed near that end of the magnet which is surrounded by the coil. The center of the diaphragm *D* is directly opposite the opening of the mouth-piece *P*.

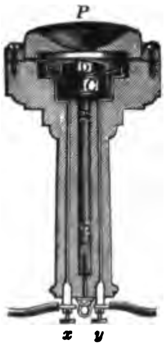


FIG. 286.

492. The Microphone Transmitter.—In practice it is found more satisfactory to employ a transmitting instrument of a different form from that of the receiving instrument. In such cases a form of transmitter called the *microphone transmitter* is employed. In the microphone transmitter the sound-waves are made to vary the electric resistance of a circuit, and thereby produce variations in the current of electricity which flows through the circuit. These variations are made to reproduce in the receiving telephone the sounds causing them.

Fig. 287 shows the construction of a simple form of microphone transmitter. A small rod *A B*, of hard carbon, sharpened at both ends, is loosely placed in small cavities in two other carbons, *C* and *D*, supported, as shown, by a piece of thin wood *E*, attached to the base *S*. The wires *a* and *b*, connected to the ends of *C* and *D*, are placed in the circuit of a battery in which is also placed a magneto-electric telephone. Any variations in the strength of the current flowing through the microphone, by producing variations in the strength of the telephone magnet,

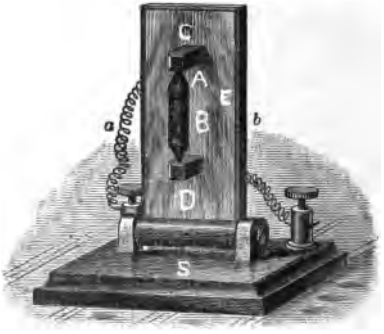


FIG. 287.

will cause movements in the diaphragm of the telephone. If a person talks near the microphone, the sound-waves will cause movements of the carbons *C* and *D*, whereby the portions of *A B* that are in contact with *C* and *D* are varied in exact accordance with the movements of the sound-waves, so that a person listening at the telephone will be able to hear all that is said.

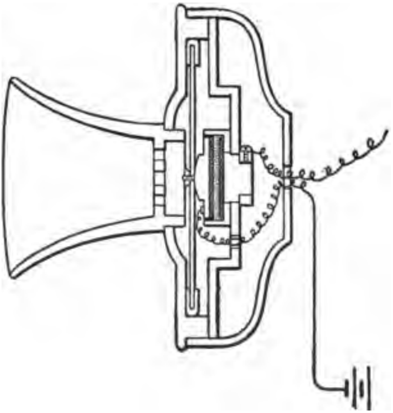


FIG. 288.

In actual practice the microphone transmitter usually consists of a quantity of loose granulated carbon, so placed back of a diaphragm as to vary the resistance of the circuit with the movements of the diaphragm by the sound-waves. As will be seen in Fig. 288, the current must pass through the grains of carbon in the carbon cup. Any variation in the resistance of the circuit will affect the amount of current flowing. The pressure produced by the sound-waves striking the diaphragm varies the resistance of the carbon and consequently the strength of the current flowing in the circuit.

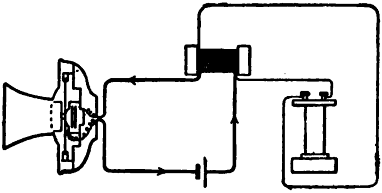


FIG. 289.

The current which goes out to the line is not that which passes through the transmitter, but an induced one, taken from the secondary of an induction coil, in the primary of which flows the current controlled by the action of the voice.

Fig. 289 shows how these connections are made. The return circuit of a modern telephone is not made through the earth, but by means of a separate wire. This is because the telephone is a very much more delicate instrument than a sounder, and so is easily affected by " stray " currents.

493. The Electro-magnetic Bell, as its name indicates, is a bell operated by the movements of the armature of an electro-magnet. In the form of electro-magnetic bell shown in Fig. 290 the armature of the electro-magnet is provided with a lever and hammer for striking the bell. The circuit connections are such that when the armature is away from the magnet poles, and, consequently, the hammer does not touch the bell, the circuit is completed through the coils of the electro-magnet. As soon as this occurs the armature is attracted and the hammer strikes the bell. But the movement of the armature breaks the circuit by moving the contact away from *w*, and the armature loses its magnetism. A spring moves the armature back again, and closes the circuit at *w*, so that the bell will continue ringing as long as the current is passing through the line circuit.

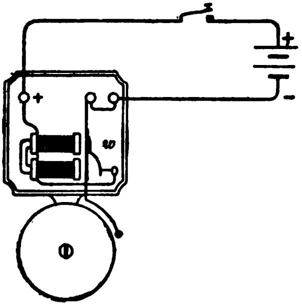


FIG. 290.

494. The Electro-magnetic Annunciator is a form of apparatus for operating a visual signal by means of push-buttons or other keys placed in a circuit. It is usually employed in hotels or houses for sending signals from one part of the building to another. Push-buttons, or other contact keys, placed in a circuit connecting the different parts of the building, operate visual signals or annunciators placed on a single annunciator board. Each of the different parts of the building is connected with a separate electro-magnet, the closing of whose circuit sets or moves a visual signal by the movement of its armature. In the annunciator shown in Fig. 291 the needle connected with the parlor has been operated by the closing of a push-button in the parlor, thus indicating a call from that room. An electro-magnetic bell is sounded at the same time, so as to call attention to the movement of the needle. A push at *P* is furnished for resetting the needle.

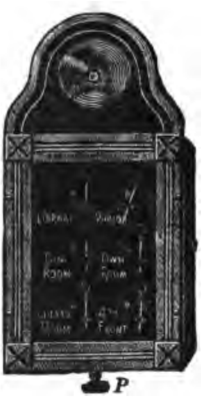


FIG. 291.

Burglar-alarm Annunciators are operated in a similar manner. In this case the burglar is made to sound the alarm unconsciously, as he either opens a door or window, or walks on contact points placed in mats or on the stairway.

495. The Electric Car.—A very common use of the electric motor is in the electric railway car. In these cars the current is supplied by means of an overhead wire or a third rail. The current is usually direct, and of about 500 volts. In most cases the current does not flow directly to the car, but is carried by the feed wire, which is connected at intervals to the trolley wire, as shown in Fig. 292. From the trolley wire

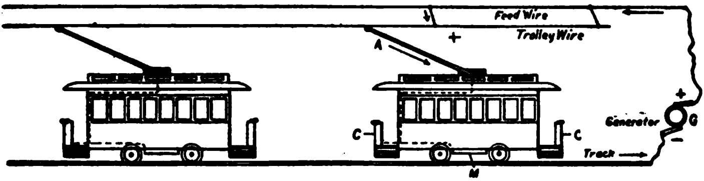


FIG. 292.

it passes by the trolley and trolley pole to the car. Here the current passes through the *controller*, C, by means of which the motorman regulates the speed of the car. The return circuit is made through the rails, which are, therefore, very carefully "bonded," that is, joined so the whole track makes a good conductor. A series of resistance coils placed under the car enables the amount of current passing through the motors to be regulated. The cars are operated in parallel on the system, each car thus offering a separate path for the current.

PROBLEMS

1. How many lamps each of resistance 220 ohms and requiring a current of 0.6 ampere can be lighted by a dynamo that has an output of 5000 watts?

2. If a dynamo is capable of doing 10 horse-power of external work, how many lamps like those in the above problem can it light?

3. A dynamo is operating 8000 incandescent lamps at 110 volts. If the lamps are all in parallel and each lamp has a resistance of 220 ohms, what is the total current furnished by the dynamo? What is the horse-power of the machine? How many kilowatts is it furnishing?

4. A lamp of a certain type to run properly needs 80 watts and 4.5 amperes. What is its resistance? If connected to a 110-volt current, the current will be too great. How much additional resistance must be added to make it burn properly?

5. What is the resistance of an arc lamp that requires a 10 ampere current and an E. M. F. of 50 volts to burn it properly?

6. Suppose that 10 such lamps are run in series in a line a half-mile long. The current is carried in a wire of copper having a diameter of 0.102 inch. What is the resistance of all the lamps? What is the resistance of the whole outside system?

7. What will have to be the potential difference at the terminals of the machine to do the work of problem 6? How many

watts are used in lighting the lamps? How many in heating the line wire?

8. The formula for the E. M. F. of a dynamo is $E = \frac{n\,k\,s}{10^8}$, where "*n*" equals the number of lines of force, "*k*" the number of conductors of the armature, and "*s*" the number of revolutions per second. If a dynamo makes 1440 revolutions per minute, has 100 conductors on the armature, and its field has 10 million lines of force, calculate its voltage.

CHAPTER XXIX

RADIATIONS

496. Ether Waves.—We have seen (Par. 252) that light is transmitted by a wave motion of the ether, the wave length being exceedingly small, varying from 0.00076 mm. for red light to 0.00038 mm. for violet light. In 1864 Clerk Maxwell, of Cambridge, England, stated that light and electrical oscillations are essentially the same in their nature, and that they are both propagated through the ether by a periodic change in its electromagnetic properties, which we call a wave. In 1888 the German, Heinrich Hertz, was able to prove by experiment that this statement was true, and he found a way of detecting the longer electrical waves, and also proved that they may be reflected and refracted just as light waves may be. These waves are much longer than those of light, some having been measured which are meters long, while the shortest which have so far been obtained are about 3 mm.

497. Production and Detection of Electro-magnetic Waves.—Whenever there is a disruptive electrical discharge, there is an accompanying disturbance of the ether which passes out as an electrical wave. The secondary of an induction coil can, therefore, be used as a source of ether waves. Hertz found that a loop of heavy wire, bent in the form of a hoop, with a small gap where the ends come together, can be used as a detector of ether waves. Under the proper conditions electric waves will cause sparks to jump across the gap of the detector. Many other detectors have been employed, in some of which the passage of the wave varies the resistance of an electrical circuit.

498. Wireless Telegraphy.—In wireless telegraphy there are employed at the transmitting station means for producing disruptive electric discharges similar to those of the Leyden jar. For this purpose an induction coil is employed. There are several different systems of wireless telegraphy, but we will describe only one, that of Marconi. The apparatus of a Marconi transmitting station is represented in Fig. 293. An induction coil (*C*) has its primary placed in the circuit of a voltaic cell (*V*) and a telegraphic key (*K*). The secondary terminals (*c*′, *c*′) of the coil are connected as shown with two polished balls of brass (*B*, *B*). One of these balls is connected to a vertical wire (*W*) extending upward into the air and the other to a ground wire or earth plate at *E*. When the key (*K*) is depressed, a spark passes between the brass balls (*B*, *B*), and an electromagnetic wave is thereby propagated through space.

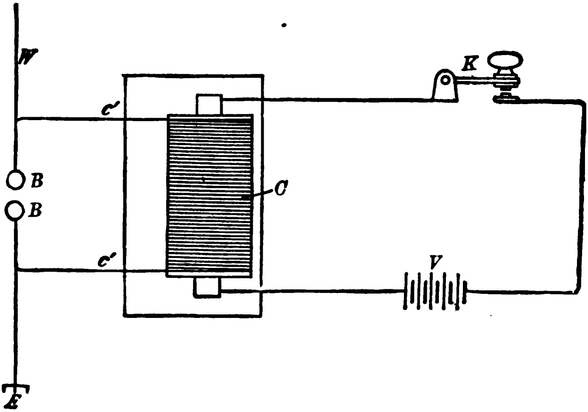


FIG. 293.—Transmitting apparatus at a Marconi wireless telegraph station.

At the receiving station there is a variety of apparatus, the most important of which is called the coherer. This consists (as shown in Fig. 294) of a small glass tube, in which a high vacuum has been obtained. Platinum wires (*W*, *W*) are sealed in the ends of the tube, as shown. Inside the tube these wires are connected to two silver pieces (*P*, *P*) that do not touch each other, but are separated by a gap of about $\frac{1}{50}$ of an inch. This gap is filled with a mixture consisting of nickel and silver filings. Under ordinary conditions the resistance of the gap, filled with the metallic filings, is too great to permit a strong current to pass through any circuit connected with the coherer. When, however, electro-magnetic waves strike against the coherer, the filings will cling together, or cohere in strings, bridging the gap, so that the resistance of the gap will become sufficiently small to permit a considerable current to pass. This decrease in the resistance will continue for some time. If, however, a slight tap or a mechanical blow be given the coherer tube, the filings will immediately fall apart, and the resistance increase so as practically to stop any flow of current.

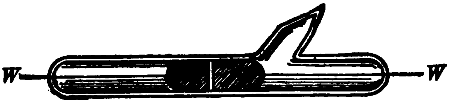


Fig. 294.—Coherer.

The coherer is connected with the circuit of one or two voltaic cells (*V*, Fig. 295), and with a fairly sensitive telegraphic relay, such as is employed in ordinary electro-magnetic telegraphy.

Assume, now, that the instruments are connected as shown in Fig. 295, and that the filings in the coherer prevent the current from the voltaic cell *V* from passing through the space or gap between the silver pieces in the coherer. If the operator at the transmitting station depresses the key for a moment, an electro-magnetic wave is propagated through space. On reaching the coherer at the receiving station, it will cause the filings immediately to cohere, thus permitting an electric current to pass through the coils of the relay *R*. This closes the circuit of a stronger battery at *B*, the current from which does two things—viz.:

(1) Operates the electro-magnet *M*, which, attracting its armature, gives a slight blow or tap to the coherer tube, thus causing the filings to fall apart, and leave the coherer ready for the next electro-magnetic wave.

(2) Operates a telegraphic recorder at *S*, and thus records the impulse produced by the momentary depression of the key at the transmitting station. If the operator at the transmitting station, instead of only momentarily depressing the key, keeps it down for a longer period of time, a dash will be produced. In this manner a series of dots and dashes, representing the letters of the Morse alphabet, can be transmitted from a distant station and recorded at the receiving station.

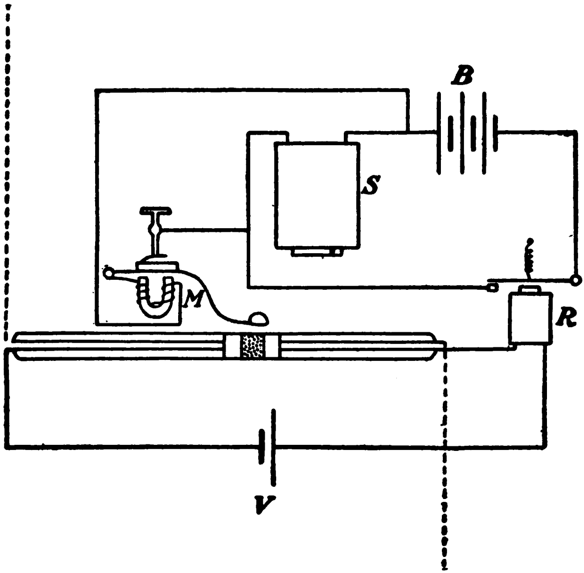


FIG. 295.—Receiving apparatus at a wireless telegraph station.

The coherer with the metal filings was invented by Branley.

It is not the only form of detector for electro-magnetic waves. There are many other forms employing other methods. The electrolytic detector is one of these in use in connection with a telephone receiver.

499. Discharge in Exhausted Tubes.—

Experiment 132.—A glass vessel (Fig. 296) provided with two metal rods, one of which is movable in an air-tight joint, and so arranged that it may be exhausted by being attached to an air-pump, is called an electrical egg. Connect the terminals to the secondary of an induction coil and it will be found that when the gap is increased, the spark will finally be unable to jump across. Now exhaust the air slowly and the discharge will be re-established. If the vacuum could be made high enough, as can be done in a small tube with sealed-in electrodes, the discharge would again stop.

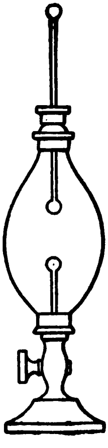


FIG. 296.—Electrical egg.

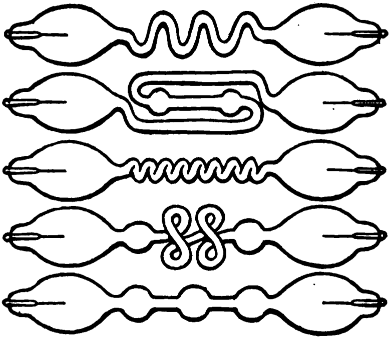


FIG. 297.—Geissler tubes.

This experiment shows that air under reduced pressure offers less resistance to the passage of the electrical discharge than air under normal pressure, but that when the pressure is very greatly reduced, it loses this conductivity.

Tubes of various forms, and often made of different kinds of glass, in which the vacuum is of a moderate amount, are known as Geissler tubes (Fig. 297). They exhibit very beautiful effects when the discharge of the secondary of an induction coil is sent through them.

500. Crookes Tubes.—A tube of the shape shown in Fig. 298 may be used to illustrate the effect of high vacua upon the electric discharge. If the vacuum is a moderate one and the terminals are connected as shown, a violet band of light will be seen passing from one electrode to the other. If the anode be changed to one of the other parts of the tube, the band will change its position and pass to the new electrode.

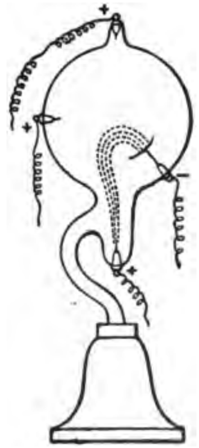


FIG. 298.

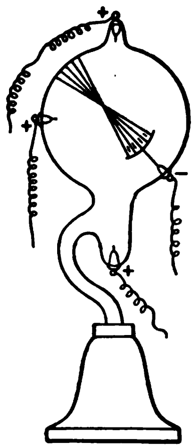


FIG. 299.

If an exactly similar tube (Fig. 299) in which a high vacuum, say, one-millionth, has been obtained is used, the action is very different. Now, no matter which anode may be used, the discharge in all cases is in a straight line from the cathode to the opposite side of the tube, and the color changes to a peculiar greenish-yellow. Such tubes, in which a high vacuum has been obtained, were first used by Sir William Crookes and are called Crookes tubes.

501. Cathode Rays.—From a study of the phenomena of Crookes tubes much has been learned about the constitution of matter. The streamings from the cathode or negative electrode are called *cathode rays.* These cathode rays consist of extremely small particles having a mass of only about $\frac{1}{1800}$ of that of a hydrogen atom, moving with a velocity between $\frac{1}{10}$ and $\frac{1}{8}$ of that of light and consist of negative electricity. They are called electrons. That the cathode rays move in straight lines is shown not only by the above experiment, but also by a beautiful one, the Maltese cross tube (Fig. 300).

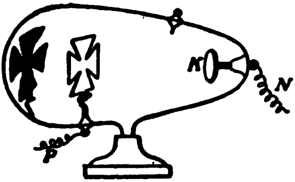


FIG. 300.

In this egg-shaped tube there is mounted an aluminum cross at the end opposite the cathode. When the discharge is sent through it, the sharp shadow of the cross is seen on the end of the tube, showing that the cathode rays move in straight lines.

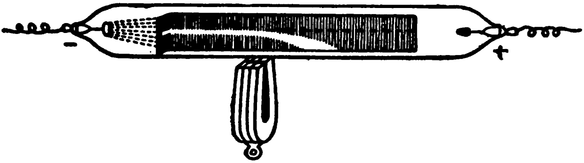
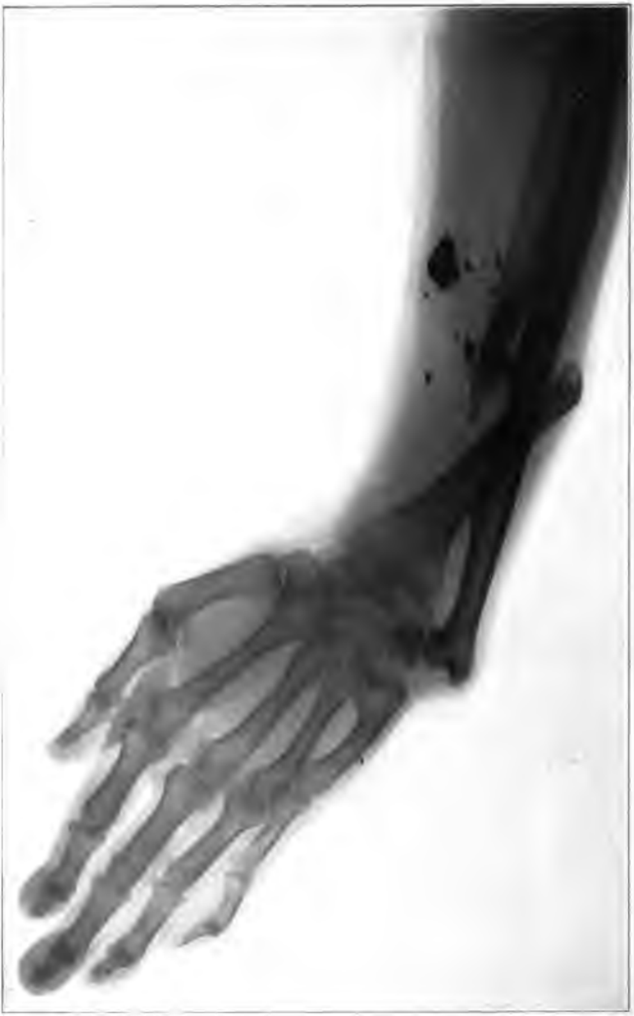


FIG. 301.

That the cathode rays carry a negative charge may be shown by the action of a magnet upon them. In the tube shown in Fig. 301 the cathode rays first pass through a narrow slit in a metal screen, and then pass across a screen covered with a fluorescent substance. A bright straight line of light is seen. If now a magnet is brought near the tube, the line of light will be attracted or repelled, depending upon which pole is presented.

502. X-Rays.—In 1895 the German scientist, Röntgen, found that a Crookes tube produced a peculiar form of radiation able



Radiograph of an arm injured near Spottsylvania Court House in 1864. Picture taken in 1908, showing injury to bones and 150 pieces of shot still in the arm.

to pass through substances opaque to ordinary light. As these were of unknown nature they were called *X*-rays. In order to produce these rays a tube of the form shown in Fig. 302 is used. The cathode is of aluminum and concave, so that the electrons projected at right angles to its surface are brought to a focus on a piece of platinum placed at such an angle that the rays are projected out of the tube where wanted. The platinum is the center from which the rays start.

The *X*-rays are now believed to be ether waves of exceedingly short wave length. Their velocity is the same as that of light.

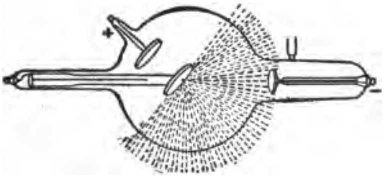


FIG. 302.

These rays can pass through many substances which are opaque to light, and can be detected by the fluorescence which they produce in certain substances, and by their effect on a photographic plate.

503. Uses of the X-Rays.—By means of *X*-rays it is now possible to locate foreign substances in the body, and also to determine the exact nature of fractures and other internal injuries. To locate such troubles the patient is exposed to the *X*-rays, and a photographic plate, protected from ordinary light by suitable means, is placed on the other side of the body. When the plate is developed, it shows a *radiograph* of the parts. The bones, being much more opaque to the rays than the flesh, are plainly seen, and any foreign body is easily noticeable, as may be seen in the plate.

X-rays have also a certain value in medicine. Certain forms of skin disease are cured by treatment with these rays. Their careless use is very dangerous, numerous instances being known where painful burns have been produced by their use, in several cases with fatal results.

504. Radioactivity.—The electrons shot off from the cathode of a Crookes tube are always identical in properties and nature no matter of what substance the cathode may be made. The charge of which they consist may be known as the atom of electricity. Their study has led some to conclude that all matter is but one manifestation of electricity.

In recent years it has been found that certain kinds of matter are continuously giving off a form of ray without any electrical stimulation being necessary. This was first noticed by Becquerel in pitchblende, an oxide of uranium. Later Prof. and Madame Curie found a new element which exhibits this property of *radioactivity*, as it is called, in a very great amouut. From this fact they gave the name *radium* to the element. It is present in the earth in very many places, but in exceedingly small quantities, and has been isolated recently.

505. Ionization.—

Experiment 133.—Charge a gold-leaf electroscope and notice that the leaves maintain their divergent position. Now set an *X*-ray tube into action in the neighborhood and the leaves quickly fall, showing that they have lost their charge.

This action is due to the ionization of the air. As produced by *X*-rays, it is believed to be caused by the exceedingly short ether waves knocking off one or more electrons from the molecules of the gases of the air. A molecule which had lost an electron would have an excess positive charge and would attract other neutral molecules to it and act as a positive ion. The electron knocked off would also attract neutral molecules and act as a negative ion. If the electroscope was positively charged, it would attract negative ions and thus have its charge neutralized. If it was negatively charged, the positive ions would be attracted, with the same effect. In the course of a short time the opposite ions in the air meet and neutralize each other, so that air thus affected soon loses its conductivity.

If some radio-active substance, as thorium oxide, uranium oxide, or a radium salt, is placed so that its rays can fall on the charged gold leaves, they are also discharged for the same reason that X-rays cause the discharge.

MENSURATION FORMULAS

$\pi = 3.1416. \qquad \pi^2 = 9.8696.$

Circumference of circle $= 2\,\pi\,r$, or $\pi\,d$.

Area of circle $= \pi\,r^2$, or $\frac{\pi}{4}\,d^2$.

Surface of sphere $= 4\,\pi\,r^2$.

Volume of sphere $= \frac{4}{3}\,\pi\,r^3 = \frac{1}{6}\,\pi\,d^3$.

Table of Velocities.

	Feet per sec.
Man swimming (highest record)	6.46
Man walking (highest record)	18.36
Man running “	30.83
Man skating “	30.61
Horse trotting “	44.55
Horse running “	62.11
Man bicycling “	76.30
Railroad train “	169.25
Sound in air at 0° C.	1090
Rifle bullet	1330
Point on equator owing to earth's rotation	1521
Centre of earth by revolution around the sun	97,601

To change feet per second to miles per hour multiply by 0.6818.

CONVERSION TABLE

To Change	To	Multiply by
Inches	Centimeters	2.5400
Centimeters	Inches	0.3937
Feet	Meters	0.3048
Meters	Feet	3.2808
Miles	Kilometers	1.6093
Kilometers	Miles	0.6213
Square inches	Square centimeters	6.4520
Square centimeters	Square inches	0.1550
Square feet	Square meters	0.0929
Square meters	Square feet	10.7640
Square yards	Square meters	0.8361
Square meters	Square yards	1.1960
Square miles	Square kilometers	2.5900
Square kilometers	Square miles	0.3861
Cubic inches	Cubic centimeters	16.3872
Cubic centimeters	Cubic inches	0.0610
Cubic yards	Cubic meters	0.7645
Cubic meters	Cubic yards	1.3079
Cubic feet	Litres	28.3170
Litres	Cubic feet	0.0353
Quarts	Litres	0.9463
Litres	Quarts	1.0566
Fluid ounces	Cubic centimeters	29.5740
Cubic centimeters	Fluid ounces	0.0338
Ounces	Grams	28.3495
Grams	Ounces	0.0352
Pounds	Kilograms	0.4535
Kilograms	Pounds	2.2046
Grains	Grams	0.0648
Grams	Grains	15.4324
Pounds weight	Dynes	444520.5800
Dynes	Pounds weight	22496×10^{-10}
Foot pounds	Kilogrammeters	0.1382
Kilogrammeters	Foot pounds	7.2330

APPENDIX

1. Derivation of Formula for Centrifugal Force.—If a body is caused to move in a circular path by means of the pull of a string, $C A$ (Fig. 303), it will tend to fly off in a tangent due to its inertia. The pull of the string prevents this and the pull of the body on the string is the centrifugal force. To find the centrifugal force we proceed as follows: Let $A E$ be the path of the body for a very short time, so that the arc, $A E$, and the chord, $A E$, may be regarded as equal in length. Then, since the body is moving with uniform velocity we have—

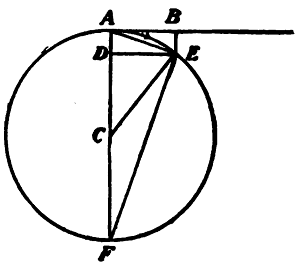


FIG. 303.

$$A E = S = vt.$$

If the body had not been pulled by the string, it would have been at B instead of at E, and has, therefore, moved through the distance $B E$, under the influence of a constant force, and, therefore, with uniform acceleration. Therefore,

$$B E = A D = S = \tfrac{1}{2}at^2.$$

In the right triangle, $A E F$, $A E$ is a mean proportional between $A D$ and $A F$, since the triangles $A E F$ and $A E D$ are similar. $A E^2 = A D \times A F$. Substituting the values as given above we have—

$$v^2t^2 = \tfrac{1}{2}\,a\,t^2 \times 2\,r.$$
$$v^2 = a \times r.$$
$$a = \frac{v^2}{r}.$$

Since $f = ma$, we have—

$$f = \frac{m \times v^2}{r}.$$

2. Formula for Kinetic Energy.—

The derivation of the formula $\frac{m v^2}{2}$ is as follows: We desire to find an algebraic expression for the energy of a moving body in terms of its mass and velocity.

$$Work = F S \qquad F = m a$$

$$\therefore W = m a S \qquad S = \frac{v^2}{2 a}$$

$$\therefore K. E. = Work = m a \times \frac{v^2}{2 a} = \frac{m v^2}{2}$$

$$W = M g \qquad M = \frac{W}{g}$$

$$\therefore K. E. = \frac{W v^2}{2 g}$$

3. Refraction in Glass.—To trace the path of a ray of light through glass having the index of refraction $\frac{3}{2}$.

1. Through a plate of glass with parallel surfaces.

Let the ray $A\ D$ (Fig. 304) meet the surface of the glass $S\ S'$ at D. Draw the normal $B\ D$. With D as a center draw two circles whose radii shall be to each other in the ratio of the index of refraction $\frac{3}{2}$. The angle of incidence is $A\ D\ B$. The sine is $e f$. In the similar triangles $e f D$ and $g h D$, $\frac{e f}{g h} = \frac{e D}{g D} = \frac{3}{2}$. Therefore, $g h$ is equal to the sine of the angle of refraction. Draw $g i$ parallel to the normal, thus making $i k$ equal to $g h$. From i, the point where the line parallel to the normal intersects the longer arc, draw the line $i D D'$. This is the path of the ray in the glass. For in the triangles $i k D$ and $i' k' D$, $i' k'$ is equal to $i k$, and is, therefore, equal to the sine of the angle of refraction. Therefore, $i' D K'$ is the angle of refraction. At D', where the ray in the glass meets the second surface $T\ T'$ erect the normal *D′ B′* and draw the two circles as before. *l′ m′* is the sine of the angle of incidence. Prolong *l′ D′* to *m*. Then, *l m* = *l′ m′*. Draw *mo* parallel to the normal. Then *n o* = *l m* = sine of the angle of incidence. Draw *D′ o v*. This will be the ray of light in the air. For in the similar triangles *D′ n o* and *D′ u v* we have $\frac{n\,o}{u\,v} = \frac{D'o}{D'v} = \frac{2}{3}$. Therefore, as *n o* is equal to the sine of the angle of incidence in the glass, *u v* is the sine of angle of refraction in the air. It will be seen that *D′ A′* is parallel to *A D*, since the refraction on passing from the glass to the air is equal to but opposite in direction to the refraction in passing from air into glass.

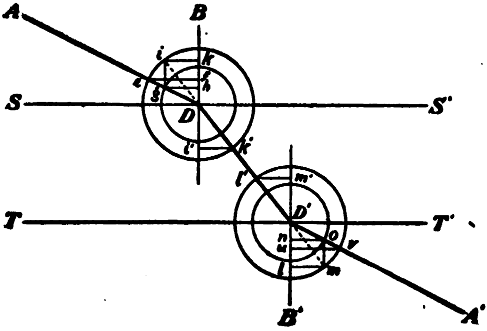


FIG. 304.

2. Through a prism.

In Fig. 305 the letters correspond to those of Fig. 304. As only a part of each circle is needed, the drawing may be simplified as follows: After drawing the incident ray *A D* and the normal *B D*, draw two arcs with radii in the ratio $\frac{3}{2}$. Where the incident ray cuts the arc of shorter radius at *g*, draw the line *g i* parallel to the normal. Where the line *g i* cuts the arc of longer radius at *i*, draw the ray *i D D′*, the path in the glass. At *D′* draw the normal *D′ B′*. With *D′* as a center draw the arcs as before. Where *D D′* prolonged cuts the arc of longer radius at *m*, draw the line *m o* parallel to the normal *D′ B′*. At *o*, where *m o* cuts the arc of shorter radius, draw *D′ o A′*. This is the path of the ray in the air. It will be seen that the ray appears to come from the point *A″*.

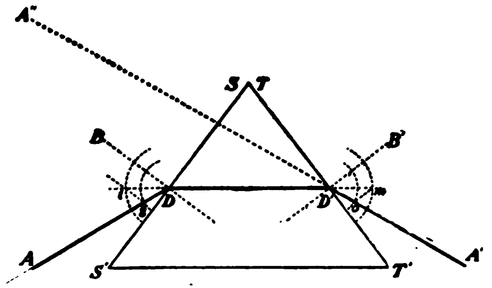


FIG. 305.

3. Through a double convex lens.

Take a point *A* (Fig. 306) on the principal axis between *C* and 2*C*. Draw the ray *A D*. Draw the normal *C′ D*. Draw the two arcs as before. Where *A D* cuts the arc of shorter radius at *g* draw *g i* parallel to the normal *C′ D B* until it cuts the arc of longer radius at *i*. Draw *i D D′*, the ray in the glass. Draw the normal *C D′*. Draw the two arcs as before. Where *D D′* prolonged cuts the arc of longer radius at *m* draw *m o* parallel to the normal *C D′* until it cuts the arc of shorter radius at *o*.

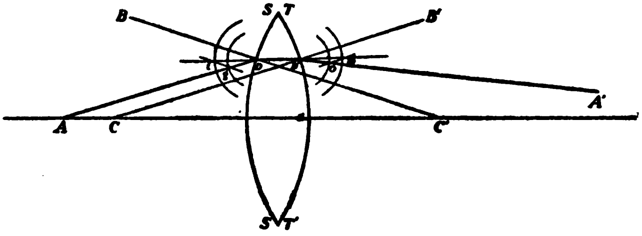


FIG. 306.

Then *D′ o A′* is the ray in air. If prolonged, it will meet the principal axis at a point beyond 2*C′*.

4. Through a double concave lens.

The method is exactly the same as in the previous drawing. Notice that a ray *A D* (Fig. 307) which is converging is made diverging after passing through this lens, and appears to come from the point *A″*, a virtual focus.

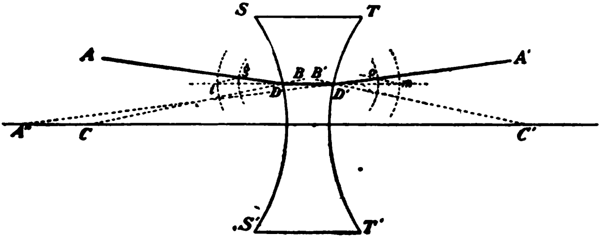


FIG. 307.

4. Derivation of Formula for Resistances in Parallel.—Let *A* and *B* be the two conductors whose resistance is known. We wish to derive an expression for their combined resistance, when placed in parallel, as shown in Fig. 308. Let *A* and *B* represent the current in each conductor, and let *a* and *b* represent the resistance of each. $C = A + B$, that is, the total current flowing is equal to the sum of that in the two conductors. If *E* is the E. M. F., then—

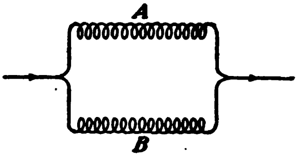


FIG. 308.

$$A = \frac{E}{a}, \text{ and } B = \frac{E}{b}, \text{ since } C = \frac{E}{R}.$$

Substituting—

$$\frac{E}{R}=\frac{E}{a}+\frac{E}{b}\ \therefore\ \frac{1}{R}=\frac{1}{a}+\frac{1}{b},$$

which may be expressed in words as follows: the reciprocal of the combined resistance is equal to the sum of the reciprocals of the separate resistances.

$$\text{Since } \frac{1}{R}=\frac{1}{a}+\frac{1}{b},\ \text{we have } R=\frac{a\,b}{a+b},$$

or, if there are two conductors, their combined resistance is equal to their product divided by their sum.

ANSWERS TO NUMERICAL PROBLEMS

Pages 19, 20.—1. 3.2815 ft. **3.** 6288 ft. **4.** 1.435 m. **5.** .00762 m.; 7.62 m.m.; 609.6 m. per sec. **6.** 486.3 m. **7.** 53 million sq. m. approx. **8.** .0007937 cm. to .0007257 cm. **9.** 55,700,000,000,000. **10.** 14,506 m.m.; .014506 km.; 1450.6 cm.

Pages 42, 43.—1. 45.18 mi. per hr. **2.** 59.73 mi. per hr. **3.** 300,196 km. per sec. **4.** 68.9 min. **5.** 75 units. **6.** 240,000 units. **7.** 5133 units. **8.** 640.3 ft. per sec. **9.** 20 lbs. wt. and 15 lbs. wt. **10.** 40 lbs. 4 ft. from 24 lb. force. **11.** 1⅞ ft. from 125 lb. lift. **12.** 141.4 lbs. wt. **13.** 126.49 lbs. wt. **14.** 11 min. 16.8 sec. **15.** 23.08 lbs. wt. **16.** 58.6 lbs. wt. **17.** 1359.6 grams wt. **18.** 795.6 lbs. wt.

Pages 63, 64.—1. 68.03 kg. **2.** 200 gr. **3.** 80.41 lbs. **4.** 76.14 lbs. **5.** 128.64 ft. per sec.; 257.28 ft.; 112.56 ft. **6.** (*a*) 7.48 sec.; (*b*) 7480 ft. **7.** 402 ft. **8.** 279.9 ft. **9.** 1.83 ft.; .55 m. **10.** 3.26 ft. **11.** 32.16. **12.** 1 : 1.41. **13.** 16 times.

Page 79.—1. 446.9 lbs. wt. **2.** .509 gr. **3.** 3.06 sq. in. **4.** Ash, by 4030 lbs. wt.

Pages 98, 99, 100.—1. 2500 ft.-lbs. **2.** 8000 ft.-lbs. **3.** 266.7 ft.-lbs. per sec. **4.** 10,000 ft.-lbs. per min. **5.** 5,702,400,000,000 ft.-lbs. **6.** 180 lbs. **7.** 1120 lbs. wt. **8.** 373.3 lbs. wt. **9.** 1000 lbs. wt. **10.** 100 lbs. wt. **11.** 80 m. **12.** 450 lbs. **13.** 2nd class, 250 lbs. wt. **14.** 4 ft. 2 in. **15.** 120. **16.** 19.8 lbs. wt. **17.** 7,600,000 H. P.

Pages 117, 118.—1. 21.67 lbs. wt. per sq. in. and 1524 gr. wt. per sq. cm. **2.** 10,404 lbs. wt. per sq. in.; 731,520 gr. wt. per sq. cm. **3.** 2194.56 kg. wt. **4.** None. **5.** 30,000 kg. **6.** 44,800 lbs. wt.; 717.6 cu. ft.; 20,320,000 cu. cm. **7.** 44,800 lbs. wt.; 699.4 cu. ft.; 19,800,000 cu. cm. **8.** 3. **9.** 33.89 ft.; 1033.2 cm. **10.** 8.89. **11.** 7.86. **12.** 1.84. **13.** .89. **14.** 18.6 cu. cm. vol. of sinker; 11.29; lead; 22.46 cu. cm. of wax. **15.** 1.42. **16.** (*a*) 3.4; (*b*) .91; (*c*) 6 c.c.. **17.** 10. **18.** .4375 cm. projects. **19.** .5. **20.** 3.08 cm.; 1.19 sp. gr.

Page 126.—1. Twice as much. **2.** 24.06 ft. per sec. **3.** 14,667 cu. cm. **4.** 161.4 ft. in each case. **5.** 161.4; 24.06; 32.08 ft. per sec.

Pages 141, 142.—1. 420 lbs. wt.; 190.5 kg. wt. **2.** 321 in.; 815.3 cm. **3.** 407.8 in.; 1035.8 cm. **4.** 43,200 lbs. wt.; 19,595.5 kg. wt. **5.** 63,815 gr.; 63.815 kg. **6.** 388,800 lbs. wt.; 176,359.7 kg. wt. **7.** 102 in. **8.** 493.4 c.c.; 506.7 c.c. **9.** 992.4 gr. wt. **10.** 176 cm. **11.** 158 gr.

Pages 158, 159.—1. 512,768. **2.** .624 sec. **3.** .642 sec. **4.** 4527 ft. **5.** 6725 ft.

Page 176.—1. 226. **2.** 1 ft. .77 in. **3.** 1 ft. .84 in. **4.** 1 ft. 5.16 in.

Pages 188, 189.—1. 4¼ years. **2.** $\frac{1}{785400}$. **3.** 3 m. from lamp. **4.** 76.9 ft. **5.** 40 ft. **6.** 27.5. **7.** 2.18 m. from stronger light. **8.** 146,900 times, approx.

Page 199.—1. 77.5°. **3.** 16 cm. **4.** 66 cm. **5.** 37.5 cm.; 75 cm. **6.** 8.57 cm. behind mirror; .57 of height of object.

Page 213.—1. $\frac{2}{\sqrt{3}}$. **3.** 13.33 cm. **4.** 20 cm. **5.** 40 in. **6.** 2.083 cm.

Page 247.—1. 11.11°. **2.** 20° C.; 48.89° C.; 96.11° C.; −62.22° C. **3.** 194° F.; 39.2° F.; 68° F.; 14° F. **4.** −37.3° F.; 674.6° F. **5.** −40°. **6.** 50.06 ft. **7.** 2.0102 m.; 161.76° C. **8.** 309.5 c.c. **9.** 91° C. **10.** .946 gr. **11.** 323° C. **12.** 140.2 c.c. **13.** 8.825 c.c.

Pages 278, 279.—1. 48,000 cal. **2.** 4324. **3.** .2002. **4.** 801.2° C. **5.** .096. **6.** 3 lbs. of snow and 11 lbs. water at 32° F. **7.** 875 gr. **8.** 80. **9.** 333⅓ gr. **10.** 5.71° C. **11.** 62,700. **12.** 35,850. **13.** 12.56. **14.** 535.2. **15.** 24.7. **16.** 7268. **17.** 2271.5 m. **18.** 119.3 cal. **19.** 2137.76 m.

Pages 290, 291.—1. 10.67. **2.** 20. **3.** 80. **4.** 6 cm.

Page 313.—1. 1.78. **2.** 20.78. **3.** 48. **5.** 23.3 sec.

Pages 333, 334.—1. 20 volts. **2.** 2 amperes. **3.** 2.33 ohms. **4.** 55. **5.** .5 ampere. **6.** 102. **7.** 516. **8.** 34,560. **9.** 10.18° C.

Pages 340, 341.—1. 8 S.; 10 P.; 3.63 amperes. **2.** 50. **3.** 1.9 volts. **4.** 10 ohms. **5.** 30 S.; 1 P.; .31 ampere.

Page 344.—1. (*a*) .079 in.; (*b*) .1118 in. **2.** 12.08 ohms. **3.** .1818 in. **4.** 3167.5 ft. **5.** .0905 ohms. **6.** 76.032 ohms.

Page 346.—1. 16.67 ohms. **2.** 9 times. **3.** 200 ohms. **4.** 44 ohms.

Page 347.—1. 40 ohms. **2.** .31 ampere. **3.** 22.5 amperes. **4.** 22.5 volts.

Page 348.—1. 18.65 ohms. **2.** 54.52 ohms.

Page 376.—1. 63. **2.** 94. **3.** 4000 amperes; 589 H. P.; 440 K. W. **4.** 3.95 ohms; 20.49 ohms. **5.** 5 ohms. **6.** 50 ohms; 52.49 ohms. **7.** 525 volts; 5000 watts; 249 watts. **8.** 240.

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